COURSE CODE: *ELE 305*

COURSE TITLE: *Electrical Machines I*

NUMBER OF UNITS: *3 Units*

COURSE DURATION: *Three hours per week*

COURSE DETAILS:

Course Coordinator: **OPEODU F.A**
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Other Lecturers: **None**

COURSE CONTENT:

COURSE REQUIREMENTS:

This is a compulsory course for all 300 level students in the College of Engineering. In view of this, students are expected to participate in all the course activities and have minimum of 75% attendance to be able to write the final examination.

READING LIST:

1. Theraja, B.L. and Theraja, A.K. "A textbook of Electrical Technology". S. Chard & Company Ltd, Ram Nagar, New Delhi – 110055 (2005).

2. Hughes, E. "Electrical and Electronic Technology". Sixth Edition. Pearson Education Limited (2002).
3. Jimmie, J.C. Electric Machines: Analysis and design applying Matlab. McGraw-Hill Higher Education, New York (2001).
4. Bhattacharya, S.K. Electrical Machines. 2nd Edition. Tata McGraw-Hill Publishing Company Limited, New Delhi (1998).
5. Fitzgedrald, A.E., Charles, K.J. and Stephen, A.U. Electric Machinery. 6th Edition. McGraw-Hill Higher Education (2003).

LECTURE NOTES

PART 1: single-phase two-winding transformer.

SINGLE PHASE TWO WINDING TRANSFORMERS

Definition: A transformer is a device by which certain desired voltage value is derived at the secondary winding terminal during its operation.

The primary and secondary windings are vital parts of a coupling between two separate electric circuits. Another component part of a transformer is the medium of coupling, which in most common applications, is iron- core. In some construction of transformers air serves as the medium in which is termed air–cored transformers.

An ore source current from the primary circuit produces a magnetic around the winding that cuts across the secondary winding through the medium thereby including an electromotive force (e.m.f.) in it. In this process, termed electromagnetic induction process the voltage ratios between the primary and secondary terminal are strictly a functions of the relative number of the two windings.

The main task of a transformer is either to transfer an ac power from the primary circuit to the secondary circuit, or to step the voltage up or down at the same frequency in either case the current in the secondary will very exactly in step with the primary.

A typical transformer is basically made up of copper or aluminum coils and laminated magnetic steel core (or iron core). There two types of transformer namely the core type of constructing.

1.1 TRANSFORMER VOLTAGE AND THE GENERAL TRANSFORMER EQUATION

1.11 TRANSFORMER ON NO- LOAD

If the secondary winding of a transformer is open circuited, the impressed voltage V_1 causes a very little current I_o t flow in the primary winding. This so called no – load current I_o is responsible for: (i) the mutual magnetic flux $\pm \alpha_m$, and (ii) the losses in the iron- core. Since the mutual flux varies in magnitude and direction between zero and $\pm \alpha_m$, e.m.f., E and E_2 are induced in the windings respectively. The voltages V_1 and E_1 are practically equal since the no- load current I_o is extremely low (about 0.02 to 0.1 of normal current).

From the expression for average induced voltage

$E_{ar} = N \ X \ \alpha_m$ volts ………………(1)

Where E_{ar} = average induced e.m.f. in a coil

N= number of turns in a coil

t = time of change of flux from zero to α_m

if I = then t = T/4= time taken for flux to attain α_m from zero. Time t corresponds to a quarter of a cycle.

E_{ar} = NX α_m/1/4f = 4FNα_m volts ………. (2)

Since for a sine wave the effective voltage E = 1.11X average voltage E_{ar}.

VOLTAGE AND CURRENT RATION OF TRANSFORMERS

Turn ration indicated- voltage ratio

$$\frac{\mathbf{E_1}}{\mathbf{E_2}} = \frac{\mathbf{N_1}}{\mathbf{N_2}}$$

In an ideal transformer, where there are no losses and no holmic resistance (efficiency = 100%), then it is generally true that the secondary load power factor pf is practically equal to the primary input power factor. Therefore

Power in = power out

$$\frac{E_1}{E_2} = \frac{I_2}{I_2}$$

and $\frac{N_1}{N_2} = \frac{I_2}{I_1}$

This implies that the voltage ratio E_1: E_2 and the turn ratio N_1: N_2 are both proportional to the inverse of current ration I_2: I_1. The primary input voltage and the secondary load voltage ratio V_1: V_2 varies about 1% /8%, depending on the character of the load and its power factor.

1.12 TRANSFORMER ON LOAD

A transformer must perform under load such that these two conditions are fulfilled: (i) the mutual flux α_m must remain practically constant; (ii) V_1I_1 must equal V_2I_2 when the primary and secondary power factors are assumed to be equal. The value and power factor angle of the load current I_2 depend in the character of the load.

The mmf produced by the secondary winding N_2I_2 tends to reduce (or oppose) the flux α that creates it – Lenz's law. Reduction of flux α goes on increase the primary net voltage (V_1-E_1) hence increases the primary current from the no-load value to a certain I_1. Fulfilling the two conditions summarized above (i) the power increases to match the power output and (ii) the primary amper-turns increase of offset the tendency on the part of the secondary ampere-turn to continue to reduce the main mutual flux α.

For the mutual flux to remain practically constant

$N_1I_1 = N_2I_2$ must be fulfilled.

I_2

VOLTAGE REGULATION OF TRANSFORMERS

The impressed voltage V_2 suffers two kinds of voltage drop before the secondary winding delivers its load voltage V_2 to the load. These are: the resistance drops in primary and secondary, and (ii) the voltage drops in primary and secondary caused by leakage fluxes. At no-load there will be no voltage drop in either winding.

Definition: the voltage change between full-load and no- load of a transformer divided by the full- load voltage is called the regulations.

$$\% \text{ reign} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 1001/2 \ldots\ldots\ldots\ldots (7)$$

1.3 EQUIVALENT CIRCUIT OF A TRANSFORMER

Where never a voltage is induced in the coil of a transformer by a changing flue through it, that induced voltage lags behind the flux by current and the flux are presumably in phase with each other, it follows that the induced voltage lags behinds the current (that creates the flux) by 90^0 electrical.

The voltage induced in the secondary winding of a transformer E_2 supplies its terminal voltage V_2 as we as takes care of the resistive voltage drop I_2R_2 and the leakages-reactance voltage drop I_1X_2. The secondary terminal voltage of a transformer may rise or fall depending on the magnitude and the character of the load unity, lagging and leading. For a unity power factor load the secondary terminal voltage drops a little; for a lagging power reduces a great deal and, for a leading power factor load the secondary terminal voltage rises above nominal value.

The scenario on the primary side of the transformer differs a little in that the impressed voltage V_1 takes a little in that the impressed voltage V_1 takes care of counter e.m.f E_1, the primary resistive voltage drop I_1X_1. All of these may be summarize in the following equations in complex form.

$$V_1 = E_1 + I_1R_1 + JI_1 X_1 = E_1 + I_1Z_1$$

$$E_2 = V_2 + I_2R_2 + JI_2X_2 = V_2 + I_2Z_2$$

Where $Z_1 = R_1 + JX_1$ and $Z_2 = R_2 + JX_2$ (complex primary and secondary impedance respectively).

REFERRED VALUES EQUIVALENT RESISTANCE, REACTANCE AND IMPEDANCE

For simplicity, primary and secondary impedance drops are combined directly to form an equivalent circuit of a transformer. Primary voltages are divided by transformer ratio “a” when the transformer is viewed from the secondary side. To view the transformer from the primary side, all voltages on the secondary side are multiplied by “a”

Since $I_1 = I_2/a$;

In secondary terms

$$I_2R_2 + \left[\frac{I_1R_1}{a}\right] = I_2R_2\left[\frac{I_2}{a} \times \frac{R_1}{a}\right] = I_2\left[R_2 + \frac{R_1}{a^2}\right]$$

$$I_2X_2 + \left[\frac{I_1X_1}{a}\right] = I_2X_2\left[\frac{I_2}{a} \times \frac{X_1}{a}\right] = I_2\left[X_2 + \frac{X_1}{a^2}\right]$$

thus $R2 + \frac{R_1}{a^2}$ = Req 1 (equivalent resistance)……………………..(8)

and

$X_2 + \frac{X_1}{a_2}$ = Xeq2 (equivalent reactance)……………………………(9)

In primary terms

$Req_1 = a^2R_2 + R_1$………………………………………………………(10)

$Xeq_1 = a^2X_2 + X_1$……………………………………………………..(11)

Equivalent impedance ingeneration is $Zeq = (R^2eq + X^2eq)^{1/2}$……… (12)

diagram

The above analysis enabled for the simplified phase diagram for a transformer where resistance and reactance drops were combined into single phasors (fig 1). In this form regulation calculations may be made more easily.

1.3.2 EQUIVALENT CIRCUIT

When a transformer is represented as ordinary series circuit that has: (i) the equivalent resistance; (ii) the equivalent leakage-reactance and (iii) the load, such can be called the equivalent circuit of a transformer. Hence, the transformer as an electric circuit, merely acts like an impedance voltage drop (fig 2). As current passes through the transformer, there is drop in voltage so that the load voltage V_2 is vectorially less than Vi/a, by the equivalent resistance and reactance drops. This equivalent drops depend on the actual load current as well as its power factor.

Diagramme 2

Example 1

A 25KVA 2300/230V distribution transformer has the following resistance and leakage reactance values: $R_1 = 0.8\Omega$; $X_1 = 3.2\ \Omega$, $R_2 = 0.009\ \Omega$; $X_2 = 0.03\ \Omega$. Determine the equivalent of resistance, reactance and impedance: (i) in secondary terms, (iii) in primary terms.

Solution

(i) Transformation ration $a = \frac{2300}{230} = 10$

$$Req_2 = 0.009 + \frac{0.8}{100} = 0.017\ \Omega$$

$$Xeq_2 = 0.03 + \frac{3.2}{100} = 0.062\ \Omega$$

$$Zeq_2 = \left[(0.017)^2 + (0.062)^2\right]^{1/2} = 0.0642\ \Omega$$

(ii) $Req_1 = (100 \times 0.009) + 0.8 = 1.7\ \Omega$

$Xeq_1 = (100 \times 0.03) + 3.2 = 6.2\ \Omega$

$Zeq_1 = \left[(1.7)2 + (6.2)^2\right]^{1/2} = 6.42\ \Omega$

Example 2

For the transformer of example 1, calculate the equivalent resistance and reactance voltage drops for a secondary load current of 109A: (i) in secondary

(iii) Terms, (iii) in primary terms

Solution

(i) In secondary terms

$I_2Req_2 = 109 \times 0.017 = 1.85V$

$I2Xeq2 = 109 \times 0.62 = 6.75V$

(ii) In primary terms

$I_1Req_1 = \frac{109}{10} \times 1.7 = 18.5V$

$I_1Xeq_1 = \frac{109}{10} \times 6.2 = 675V$

Example 3

Using the data of example 1 and 2, calculate the % equ: (i) for unity p.f.; (ii) for a lagging p.f of 0.8 and; (iii) for a leading p.f of 0.866.

Solution

(i) $V_1 = \left[(2300 + 18.5)^2 + (67.5)\right]^{1/2} = 2320V$

$$\%regn\ (at\ p.f = 1) = \frac{2320 - 2300}{2300} \times 100\% = 0.87\%$$

(ii) $$V_1 = \left[(2300 \times 0.8) + 18.5)^2 + (2300 \times 0.6) + 67.5)^2\right]^{1/2} = 2360V$$

$$\%\ regn.\ (pf = 0.8lag) = \frac{2360-2300}{2300} \times 100\% = 2.61\%$$

(iii) $$V_1 = \left[(2300 \times 0.866) + 18.5)^2 + (2300 \times 0.5) - 67.5)^2\right]^{1/2} = -0.87\%$$

1.4 TRANSFORMER TESTS

1.4.1 SHORT-CIRCUIT TEST (S.C.T)

Short-circuit test is generally performed to determine experimentally the values of: (i) The equivalent tresitance, impedance, and reactance. Because the secondary terminal is short circuited, 5% impressed voltage must be applied to the primary, which also brings the mutual flux of down in the same proportion. In this way the windings carry rated currents without a load and a pattern of leakage fluxes is simulated in both windings. Short-circuit test is an economical method of determining experimentally: (i) the copper (Cu) loss at full-load (and at any desired load)- this enables determine transformer efficiency,

(iii) The percent regulation (% regn)

At $V_2 = 0$, V_1/a merely overcomes the full-load I_2Req_2 and I_2Xeq_2 voltage drops.

Since core loss is nearly proportional to the square of the mutual flux, the flux is practically zero. The absence of power output and core loss in their experiment means that the only power registered is the Cu loss.

All the measuring instruments are connected to the primary (usually the HV side) with the ammeter measuring the rated current. The LV side will also definitely carry rated current by transformer action.

Note

Low-range measuring instruments are used because:

(i) The HV side is expected to carry the lower current for the ammeter (ii) 5% of the rated impressed voltage is taken by the voltmeter and; (iii) the watrmeter reads only copper loss of both windings –less then 3% of he rated output.

From the experimental data: Watts, Amps and volta, the values of equivalent resistance, impedance and, reactance is calculated in terms of he HV side thus;

$$Req = \frac{Psc}{I^2sc} \quad \text{...(13)}$$

$$Zeq = \frac{Vsc}{Isc} \quad \text{...(14)}$$

$$Xeq = \sqrt{Zeq - Req} \quad \text{................................(15)}$$

Where Psc, Isc and Vsc are short-circuit watts, amps, and volts respectively.

Example 4

The following data were obtained when a short-circuit test was performed on a 100KVA 2400/240V distribution transformer: Vsc 72V; Isc = 41.6A; Psc = 1180W. All instruments were placed on the HV side, and the LV side was short-circuited. Determine:

(i) the equivalent resistance the equivalent impedance and the equivalent reactance; (iii) Percent regulation at a p.f of 0.75 lagging.

Solution

(i) $$Re = \frac{1180}{(41.6)^2} = 0.682\ \Omega$$

$$Zeq = \frac{72}{41.6} = 1.73\ \Omega$$

$$Xeq = \left[(1.73)^2 + (0.682)^2\right]^{1/2} = 1.59\ \Omega$$

Since copper losses vary as the square of the current, these losses therefore rise or drop sharply above or below the full-load value, when the load is lower or higher than the rated KVA respectively. For an 0.5 rated KVA, the losses become 0.25 full-load value; at 1.5rated KVA, the become 2.25 full load losses.

Example 5

For the transformer of example 4, calculate the Cu losses when the load is (i) 125KVA; (ii) 75KVA, (iii) 85KW at a p.f of 0.772.

Solution

(i) $$\left[\frac{125}{100}\right]^2 \text{ X } 1180 = 1845\text{W}$$

(ii) $$\left[\frac{75}{100}\right]^2 \text{ X } 1180 = 663\text{W}$$

(iii) $$\left[\frac{85/0.772}{100}\right]^2 \text{ X } 1180 = 1430\text{W}$$

Example 6

For what KW load, at a p.f of 0.71 will the Cu losses in the transformer of example 4 be 1500w?

Solution

$$1500 = 1180 \left(\frac{Kw/0.71}{100}\right)^{2}$$

$$Kw = 100 \times 0.71 \left(\frac{1500}{1180}\right)^{1/2} = 80kw$$

1.4.2 OPEN-CIRCUIT TEST (O.C.T)

The HV side is open-circuited in this experiment while rated primary voltage is applied to the LV side. Ammeter connected to the primary records no-load current I0, which produces the normal mutual flux ǿ and the core-losses (Hysteresis and Eddy-current losses). Since I0 is low Cu losses is negligible, so the wattmeter reads only core-losses. Note that instruments are safer when connected to the LV side. Also, proper core-loss is measured only when the rated impressed voltage is captured during the test.

Core-loss $Pfe = Pu + Pe$

Where Pfe, Pn and Pe are Core-loss, hysteresis loss, and eddy-current loses respectively. For a given impressed voltage Vi, edy-current loss is independent of the frequency, but is directly proportional to the square of the impressed emf.

$$Pfe = K_2E_2 \qquad (16)$$

Hysteresis loss does depend on both applied voltage and its frequency

$$Pn = K^1 \frac{E^{1.6}}{f^{0.6}}$$

1.4.3 Regulation using short-circuit test data

Since there is no output voltage in short-circuit, the short-circuit voltage Vsc that completely overcomes the equivalent impedance Zeq of the transformer is actually the impedance voltage drop at full-load. As a percentage of the rated transformer voltage, in terms of the side on which the test is performed, it is called the %IZ drop and may be expressed as;

$$\%IZ = \frac{Vsc}{Vrated} \quad X\ 100\% \text{............................}(7)$$

Definition: the short-circuit voltage of a transformer s that primary winding voltage at which the transformer itself consumes the rated full-load current when the secondary winding is short-circuited or fixed with another ammeter.

Transformers are designed for certain voltages and currents and short-circuit voltages for transformers differ according to their ratings. Usually relative short-circuit voltage are quoted as percentages of the rated voltages (as in equation 17).

Short-circuit voltage is of importance in determining the internal impedance of a transformer, its consumed power W and its angle of phase difference p. it is also important in calculating short-circuit current Isc and when transformers are to be connect din parallel.

Power input to the short-circuited transformer used entirely to supply Cu losses

$$Psc = I^2_{fl}\ Req \text{ or } I^2_2\ Req$$

As a percentage of the VA rating of the transformer

$$Psc = \left[(I^2_{fl}Req)/ (Vrated \times I_{fl})\right] \times 100$$

Percent I Req drop or % IR drop

$$\%IR = \frac{I^2_{fl}\ Req}{Vrated \times I_{fl}} \times 100\%$$

$$= \frac{Ifl\ Req}{Vfl} \times 100\% = \frac{Psc}{VArated}$$

Having established the values of %IR and %IX from the short-circuit test, they may be substituted from the short-circuit test, they may be substituted in an extremely convenient equation to determine the % regn of a transformer.

$$\% regn = \% IRcos + \% IX \sin \alpha + \frac{(\%IXcos4 - \% IR \sin 4)^2}{200} \ldots\ldots..(18)$$

The power factor angle 4 is positive for a lagging power factor load and negative for a leading power factor load.

Example 6

Using the data given in example 4, determine the % regn of the transformer for: (i) unity p.f load, (ii) an 0.8 lagging p.f load, (iii) an 0.866 leading p.f load.

Solution

$V_1 = 2400V$, $KVA = 100000KVA$; $Vsc = 72V$;

$Isc = 41.6A$; and $Psc = 1180W$

$$\%Z = \left[\frac{72}{2400}\right] \times 100^0 = 3\%$$

$$\%R = \left[\frac{1180}{100000}\right] \times 100\% = 1.18\%$$

$$\%X = \sqrt{32 - (1.18)^2} = 2.76\%$$

When p.f =1, cos α =1 (α = 0) and sin 4 = 0

$$\% \text{ regn} = (1.18 \times 1) + (2.76 \times 0) + \frac{[(2.76 \times 1) - (1.18 \times 0)]^2}{200}$$

$$= 1.18+0+0.38 = 1.218\%$$

(ii) When p.f = 0.8lagging, cos 4 = 0.8 and sin α = 0.6

$$\% \text{ regn} = (1.18 \times 0.8) + (2.76 \times 0.6) + \frac{[(2.76 \times 0.8) - (1.18 \times 0.6)]^2}{200}$$

$$=0.944 + 1.656 + 0.0075 = 2.51\%$$

(iii) When p.f = 0.866 leading; cos α = 0.866 and sin a = 0.5.

$$\% \text{ regn} = \left[(1.18 \times 0.866) - (2.76 \times 0.5) + \frac{(2.76 \times 0.866) + (1.18 \times 0.5)}{200}\right]^2$$

$$= 1.022 - 1.38 + 0.0149 = -0.343\%$$

Transformer Efficiency (1)

The fact that the power output of a static transformer is less that the power input-only in the losses-implies that its efficiency η is less than 100%. Moreover, the efficiency of a transformer is the ratio between the active power output and the active power input, even though losses are proportional to the volt-ampere.

$$\text{Efficiency } \eta = \frac{P \text{ out}}{P \text{ inp}}$$

The active power input is composed of:

(i) The active power output, (ii) the core-loss (no-load measurement) Pfe, and the winding copper Cu loss (short-circuit measurement) Psc.

$$\eta = \frac{Pout}{Pout + Pfe + Psc}$$

P out = V2 I2 Cos α2 Watts; total Cu loss = Psc = $I^2_2Ro_2$

Iron (Core) loss = Pfe Watts

Total losses = $P_{sc} + P_{fe} = I^2{}_2 Ro_2 + P_{fe} = P_{losses}$

Power input $P_{inp} = P_{output} + P_{sc} + P_{fe}$

$$= \frac{V_2I_2 \cos \alpha_2}{V_2I_2\cos\alpha_2 + I22\ Ro_2 + P_{fe}}$$

$$\eta = \frac{Pinp - Plosses}{Pinp} = 1 - \frac{Plosses}{Pinp}$$

$$= 1 - \frac{I^2{}_2\ Ro_2 + P_{fe}}{V_2I_2\cos \alpha_2 + I^2{}_2 Ro_2 + P_{fe}} \quad \text{..........................(20)}$$

Maximum efficiency

As the load of a transformer in operation increases from zero to rated output and above, the efficiency rises to a maximum and then proceeds to drop off. This is because efficiency calculation for progressively increasing values of load that rise linearly involves two kinds of losses- iron losses and Cu losses.

$$I^2{}_2Req_2 = Pfe$$

$$I_2 = \frac{P_{fe}}{Req_1} \quad \text{condition for maximum efficiency}$$

Multiply in both sides by secondary kilovolt and the right side by I_{fl}/I_{fl}

$$\frac{V_2 I_2}{100} = \frac{V_2 I_{fl}}{1000 I_{fl}} \frac{P_{fe}}{Req2} = \frac{V_2 I_{fl}}{1000} \sqrt{\frac{P_{fl}}{Req_2}}$$

= KVA load for maximum efficiency

Then $\frac{V_2 I_{fl}}{1000}$ = KVA rating of transformer

and $I^2_{fl}\, Req_2$ = full-load Cu losses P_{sc}

Hence KVA max.eff = KVA rated $\frac{P_{fe}}{P_{sc}}$ ……………………………(21)

All-day efficiency

Definition: all-day efficiency of a transformer is the ratio of energy (in KWH) delivered by the transformer in a 24-hr period to the input energy during the same period of time. Transformers operate at maximum efficiency ηmax ($P_{sc} = P_{fe}$) in a range of about 0.5 their rated KVA. Since the core losses of distribution transformers are supplied continuously as they deliver light loads during the greater part of the day, such transformers are designed in practice to minimize core losses. Based on such operating conditions, the all-day efficiency of a transformer is adjudged higher than its full-load efficiency. Comparing the all-ay efficiencies of transformers is much more satisfactory, since this rating takes into account operation over a 24-hr period. In order to determine the all-day efficiency, it is essential to know how the load varies from hour to hour during the day.

Example 7

A 5KVA 2300/230V 50Hz standard distribution transformer was tested and the following results were obtained: S.C test input = 112W; O.C. test input = 40W. Determine the efficiencies of the transformer for a p.f = 0.8 for the following fractions of the rated KVA: 0.25, 0.5, 0.75, 1, 1.25, 1.5. Tabulate the results

Solution

	Losses			**Watts**		Percent efficiency
KVA output = 1000Va	Core	Copper	Total	Output	Input	Efficiency
0	40	0	40	0	40	0
1250	40	7	47	1000	1047	95.51
2500	40	28	68	2000	2068	96.71
3750	40	63	103	3000	3103	96.68
5000	40	112	152	4000	4152	96.34
6250	40	175	215	5000	5215	95.87
7500	40	252	292	6000	6291	95.36

Example 8

The transformer of example 7 operates with the following loads during a 24-hr period: 1½ rated KVA; p.f =0.8, 1hr; 1¼ rated KVA, p.f-0.8, 2hr, rated KVA, p.f =0.9, 3hr; ½ rated KVA, p.f =1, 6hrs ¼ rated KVA. P.f =1.0, 8hr; no-load, 4hr. deermine the all-day efficiency.

Solution

Energy output		Energy losses, KWH	
W_1 = 1.5 x 5x0.8x1 =	6.0	(1 ½)2 x 0.112 x 1 =	0.252
W_2 = 1.2 x 5 x 0.8 x2 =	10.0	(1 ¼)2 x 0.112 x 2 =	0.350
W_3 = 1 x 5 x 0.9 x 3 =	13.5	1 x 0.112 x 3 =	0.336
W_6 = 0.5 x 5 x 1.0x6 =	15.0	$(1/2)^2$ x0.112x6 =	0.168
W_8 = 0.25 x 5 x 1.0 x 8 =	10.0	(1/4)2 x 0.112 x 8 =	0.056
Total ……………………..	**54.5**	iron = 0.04 x 24 =	0.960
		Total ……………….	**2.122**

$$\text{All-day efficiency} = 1 - \frac{2.122}{54.5+2.122} \times 100 = 96.25\%$$

2.0 AUTOTRANSFORMERS

In autotransformers the two windings are both magnetically and electrically connected. In autotransformers the laws governing conventional two-winding transformers apply equally well.

Diagram

Fig 3: current and voltage relations in an autotransformer

The input voltage is connected to the complete winding ac and the load connected across only a portion of the winding bc (fig 3).

$$\frac{V_2}{V_1} = \frac{Nbc}{Nac}$$

If, for convenience a unity power factor and a lossless auto-transformer is assumed

$I_2 = V_2/RL$ and $V_1I_1 = V_2I_2$ respectively.

The auto-transformer acts exactly like a two-winding transformer if, from the stand point of transformer action, it is considered that the portion of the winding ab is the primary and bc is the secondary. If that is the case, then the N1I1 = N2I2 relationship is foundermental to the operation of all transformers. Concerning fig.3 Nab I1 = Nbc (I_2-I_1)

Proof: $Nbc\,(I_2 - I_1) = (Nac - Nab)\ (I_2 - I_1)$

$= NacI_2 - NacI_1 - NabI_2 + NabI_1$

But $\frac{Nac}{Nbc} = \frac{I_1}{I_1}$

Therefore, $I_1 = \frac{Nbc}{Nac} I_2$

Substituting for I1

$$Nbc\,(I_2-I_1) = NacI_2 - Nac \times \frac{Nbc}{Nac} I_2 - NabI_2^{+}$$

$Nab\,I_1 = (Nac - Nbc)I_2 - NabI_2 + NabI_1$

Which proves that $Nbc\,(I_2 - I_1) = NabI_1$

The foregoing indicates that the power transformed is

P_{trans} = (Vac - Vbc) I_1 = V (I_1 - I_2)………………………..(22)

Since a = V_1/V_2 and V_2 = V_1/a

P_{trans} = (V_1 –V_1/a)I_1 = V_1I_1 (1-1/a)

Hence P_{trans} = Power input X (1 - 1/a) ……………………………(23)

Example 9

A conventional 3KVA 2200/220-V distribution transformer is to be connected as an autotransformer to step-down the voltage form 2420 to 2200. (i) Make a wiring diagram showing how the transformer should be connected. (ii) with the transformer used to transform rated power, calculate the total power input.

Solution

Diagrame

Fig.4 wiring diagram for solution to example 9

(ii) $a = \frac{2420}{2200} = 1.1$

$$\text{Power input} = \frac{\text{Ptrans}}{(1 - {}^{1}/_{1.1})} = 33000\text{W}$$

This example only shows that an auto-transformer of a given physical dimension is capable of handling much more power than an equivalent two-winding transformer. It has been shown that a 3KVA transformer is capable of taking care of 11 times its rating an autotransformers, thus transforms, by transformer action, a fraction of the total power; the power that is not transformed is conducted directly to the load and does actually participating in the transformer action.

Autotransformers are cheaper in first cost that conventional two- winding transformers of the same rating. They possess higher regulation capacity voltage does not drop so much for the same load and they operate at higher efficiencies. However, they are considered unsafe for use in ordinary distribution circuits because the HV primary circuit is directly connected to the secondary circuit , on he other hand for connecting one HV system, say 2200V, to another, say 13800V, they are especially suitable, for the reasons given above. They are very frequently used ijn connection with the starting of certain types of ac motor, such that lower than line voltage is applicable during starting period.

3.0 INSTRUMENT TRANSFORMERS

Definition: Transformers are devices used in power systems where it is necessary to measure comparatively high voltage and high current values with standard low-range voltmeters and ammeters respectively. In practice, current transformer are usually connected to ordinary 5A ammeters, while potential transformers are generally employs with standard 150V voltmeters. Connected in series in the circuit transformer has a primary coil of one or more turns of heavy wire. The secondary has a great many turns of comparatively in across the ammeter terminals.

In such an instrument, for a current step down of ratio 100:5 there will be voltage step-up

Example 10

It is desired to measure a current of about 150A to 180A. (i) If a 5A ammeter is to be used in conjunction with a current transformer, what should be the ratio of the latter? With this transformer, what should the instrument deflection be multiplied by to give the true line current?

Solution

i. Use 200:5 transformer

ii. Multiply the instrument deflection by 40

An extremely practical design of current transformer is the clapm- on or type where the conductor carrying current acts as the single-turn primary and the secondary is accurately wound, permanently connected to the ammeter that is conveniently mounted in the handle.

In this style, provision is made for changing the ratio to permit full-scale deflection of 10, 25, 50, 100, 250 Amps by moving pointer over a dial indicating maximum current to be measured.

An important of the current transformer operation is that its secondary must never be allowed to be open-circuited as this may lead to the saturation of the core. The unavailability of the secondary ampere-turns to react with the primary ampere-turn in open secondary jerks up the magnetizing current. This presents a residual flux in the core, and an increased excitation appears when the transformer comes into operation again invalidating the original calibrations of the instrument.

Potential transformer

These are carefully designed, extremely accurate-ratio step- down transformers. They are used with standard low-range volt meters, he deflection of which, when multiplied by the ratio of transformation, gives the true voltage on the HV side. In general they differ very little from the ordinary two winding transformer except that they handle a very little amount of power. Since their secondaries are required to operate instruments and sometimes relays and pilot lights in electric circuits, they ordinary have ratings of 40 to 100 KVA. Common ratios of transformation are: 10.1, 20.1, 40.1, 80.1, 100.1, 120.1 and higher. Primary voltages are indirectly indicated using ordinary 150V voltmeters when connected to the secondary's of such transformers.

Diagram

Fig 6 Wiring connection for measuring a HV with a potential transformer and a 150V voltmeter

For safety, the secondary circuit is extremely and well insulated from the HV primary and well grounded.

Example ii

A potential transformer and a 150V voltmeter are connected as in fig 6 for the measurement of the HV side voltage of a distribution transformer. If the voltmeter deflection is 133, what is the instrument line voltage?

Solution

V_{line} = 50 X 1333= 6,650V

4.0 THREE-PHASE TRANSFORMER

In 3 phase power systems comprising generation transmission, and distribution, the major intermediate equipment is the three- phase transformer. In the past three single-phase transformers were usually interconnected instead of single three-phase transformers. To satisfactory accomplish the former the three single- phase transformer must have similar KVA ratings, similar collage ratings and identical polar ties. The following advantages are associated to employing the services of a single three- phase over a three single-phase transformer. It occupies less floor space for equal rating; weighs less; cost about 15% less; and only one unit is to be connected and handles. One main disadvantage in single three-phase transformer is that should any one phase be disable, the whole transformer has to be removed from service for repairs four general standard connection methods for the transformer. Windings in various star (Y) and Delta (D) are: Y-Y, Δ-Δ, Δ-Y,& Y-Δ (as shown in fig 8 below)

The YY connection (O^0 angular displacement)

Such connections find application in interconnection of high tension power systems. Minimum insulation is required as voltage is only 1/ 3 of line voltage. The line voltage ratio of the HV and LV is the same as that of the 30^o exists between the line and phase voltages of both sides. When the neutral of the primaries of such transformers are grounded (a way of automatically connecting the commonly grounded Y- connected generator neutral), the effect of unbalanced load at the secondary side is corrected.

The ΔΔ connection (O^0 angular displacement) they find application in systems where voltages are low and will not require much insulations. The primary and secondary line \ voltage ration is the same as that of each primary and secondary phase voltage transformation ratio. There is no angular displacement between primary and secondary windings and no internal phase shift between phase an line.

Voltages. Third harmonic component of magnetizing current flows in the D- connected primaries without flowing in the wires. The three-phase voltages remain practically constant regardless of load imbalance. System can continue to operate in open delta should a phase go out.

The ΔY connection (30^0 angular displacement). They find application in the starting end of high tension transmission systems. Here insulation is stressed to the extent of 58% of line-to-line voltage. Transformer represents line voltage in the primary insulation will be provided for the secondary (Y) of a primary and secondary line voltages and line currents are 30^0 electrical out of phase with each other. The voltage ratio of the line voltages will no longer be the same as the ratio of transformer of each phase. The ratio of the line –to-line voltages, high to low will be 3 x q, $V_H : V_L$ 1.73.xa D.Y connection

Is mainly used in secondary systems where the secondary LV side distributes power (with 3-phase 4- wire) to end user at 230V phase-to-neutral and 415v phase-to-phase.

The YΔ connection (30^0 angular displacement). They are found at step- down transmission lines. The ratio between secondary and primary line voltages is 1/3 times the transformation ration of each phase. There exists a 30^0 electrical shift between the primary and secondary line voltages.

Example 12

Three 10.0 step down transformer are connected Y on the primary side and D on the secondary side if the primary line-to-line voltage is 3,980 V and the secondary delivers rated balanced three phase load of 180 kw at pf of 0.8, calculate.

(i) The line voltage on the secondary side; (ii) the current in each transformer winding on the secondary side (iii) in each line current on the secondary side,

(iv) The current in each of the transformer windings on the primary side ie the primary line current; (v) the KVA rating of each transformer.

Solution

V_2 since load is balanced, each transformer delivers one third of the total load i.e 180/3 = 60kw at p.f = o.s. therefore.

I_{2ph} (transformer winding) = 60000 = 326A

230 x 0.8

I_{2L} (line current) = 3 x I_2ph = 3 x 3326 = 565A

I_1 (line current) = 3 x I_{2ph} = 3 x 326

I_1 = 60000

(13980/3 x 0.8

KVA per transformer = 75.