TRANSFORMERS

WHY TRANSFORMERS?

- AC can be easily generated using rotational mechanical energy as input. AC voltages can also be easily transformed into higher or lower values.
- The voltage transformer can be thought of as an electrical component rather than an electronic component.
- The voltage transformer, essentially speaking, is a stationary electromagnetic passive device that works on the Faraday's law of of induction by converting electrical voltage from one value to another.
- Transmission of electric power over long distances is more economical if higher voltages are used. Hence the need for 'step-up' transformers. At the receiving end, the higher voltages need to be brought down to lower values, for 'distribution' purposes. Hence the need for a 'step down' transformer.

HOW?

- Mutual induction is the process by which a coil of wire magnetically induces a voltage into another coil located in the vicinity. Obviously, the concept does not normally work for DC.
- Transformers can not change the frequency of the voltage being inputted.
- A single-phase transformer basically consists of two coils of conducting wire (Aluminum, Copper, etc.), one called ‘primary winding’ and other called ‘secondary winding’. The coils are not in electrical contact with each other. Instead, they are wrapped together around a common closed magnetic iron circuit called ‘core’. This soft iron core is not solid but made up of individual laminations connected together (to reduce losses).

HOW?

- The two coil windings are electrically insulated from each other. However, they are magnetically linked through the common ‘core’. This allows electrical power to be transferred from one coil to another.
- When an AC current passes through the primary winding, a magnetic field is developed in the core which induces a voltage in the secondary winding.
- A ratio exists between the number of turns on the primary coil and that on the secondary coil. This ratio is known as ‘transformation ratio’, ‘turns ratio’, etc.

NAMEPLATE

- THE NAMEPLATE OF A TYPICAL TRANSFORMER CONTAINS THE FOLLOWING INFO (AT LEAST):

  1. Recommended primary and secondary voltages of operation
  2. KVA Rating (Full-Load)
  3. Recommended Frequency of Operation

  Note that apparent power S (KVA) is specified. The consumed power (P) and the reactive power (Q) will be determined by the power factor of the load to which the secondary winding is connected.

Transformation Ratio

- Primary Voltage divided by Secondary Voltage = Number of turns in primary winding divided by Number of turns in secondary winding.
- However, Primary Current divided by Secondary Current = Number of turns in secondary winding divided by Number of turns in primary winding.
- THE ABOVE TWO STATEMENTS ARE FULLY TRUE FOR ONLY THE IDEAL LOSSLESS TRANSFORMER. They, however, serve as useful guidelines for real-life lossy transformers, too.

TRANSFORMER BASICS

- An alternating-current emf device in a certain circuit has a smaller resistance than that of the resistive load in the circuit. This is a fact of life based on how AC generators are designed and built and what loads they have to deal with, once put in real-world usage.

TRANSFORMER BASICS

- To increase the transfer of energy from the device to the load, a transformer will be connected between the two. See one example below in Figure 1.

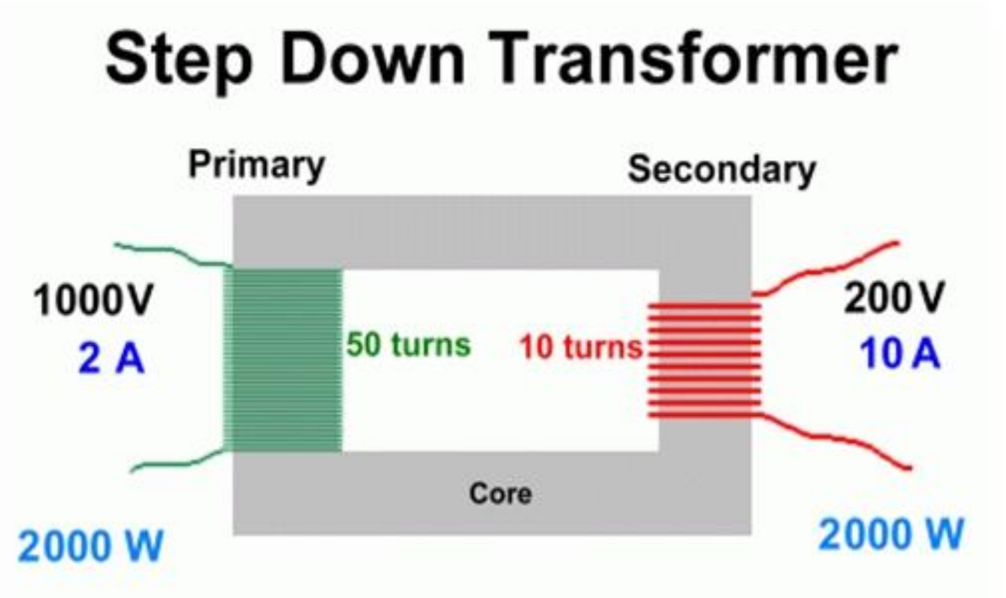


Figure 1 A Step Down Transformer designed for primary voltage V_p=1000V (RMS value) and secondary voltage V_s=200V (RMS value)

TRANSFORMER BASICS

- The transformer in Figure 1 is designed to take 1000 volts RMS at input (primary winding) and produce 200 volts RMS at output (secondary winding).
- The number of turns in the primary winding (N_p) is five times higher than the same in the secondary winding (N_s).
- The actual value of N_p is determined by several factors like how much magnetic flux is generated in the core of the transformer, how much primary voltage is the transformer designed for, what is the intended frequency of operation, etc. I can supply you the exact equation if necessary.

TRANSFORMER BASICS

- In an ideal lossless transformer, the product of primary current I_p and primary voltage V_p is equal to the product of secondary current I_s and secondary voltage V_s.
- Hence, the secondary current for the transformer in Figure 1 is five times higher than the primary current.
- For a step-up transformer, $V_p<V_s$, $I_p>I_s$, and $N_p<N_s$.
- For a step-down transformer, $V_p>V_s$, $I_p<I_s$, and $N_p>N_s$.
- Loss-less transformer is being referred to as ‘ideal’ transformer in sample problem 31.08.

TRANSFORMER BASICS

- The power factor of the load connected to the transformer's secondary winding is unity if the load contains only resistances. If the load contains inductors/capacitors too, the power factor will be less than unity.
- For a purely-resistive load (unity power factor case), the average power dissipated in the load (also known as consumed power in load) is $P=V_sI_s$ Watts where V_s is secondary voltage (RMS value) in volts and I_s is secondary current (RMS value) in Amperes.
- For the ideal loss-less transformer, $V_p/V_s = N_p/N_s = I_s/I_p$ where N_p/N_s is known as the turns-ratio of the transformer. The turns-ratio is frequently given the symbol a.
- For a complex load (that is, load containing resistors, inductors, and capacitors), we define power factor p.f.= cos φ where φ is known as the 'power factor angle' and will be explained a bit later in this PPT.
- The numerical value of the power factor is always less than unity for a complex load.

TRANSFORMER BASICS

- The complex load impedance is written in ohm but its value is a complex number.
- We write the complex load impedance as $Z = R + j X$ where R, the real part, is known as resistance and X, the imaginary part, is known as reactance.
- Both R and X are measured in ohm too.
- R generally has a positive value.
- X can have a negative value (capacitive load) or a positive value (inductive load).

TRANSFORMER BASICS

- For a capacitor of value C farad, the capacitive reactance is $X_c=1/(2\pi fC)$ ohm where f is the frequency of operation.
- For an inductor of value L henry, the inductive reactance is $X_L=2\pi fL$ ohm where f is the frequency of operation.
- For a load containing resistances, inductances, and capacitances, we need to figure out the total value of complex load impedance Z.
- Z will, in general, have a real part R and an imaginary part X.
- The power factor angle φ is related to R and X of a load by $\tan \varphi = X/R$.
- For a purely-resistive load, X=0. Hence $\varphi = 0$ and power factor $\cos \varphi = 1$.

TRANSFORMER BASICS

- For a purely reactive load, R=0. Hence $\varphi=\pi/2$ radians. Hence, power factor is equal to zero.
- If the sign of X is positive (inductive reactance), the power factor is known as ‘lagging’ and if the sign of X is negative (capacitive reactance), the power factor is known as ‘leading’.
- Leading power factor implies that the current is leading the voltage.
- Lagging power factor implies that the current is lagging the voltage.
- SAMPLE PROBLEM 31.08 is a straightforward one.

SAMPLE PROBLEM 31.08

- PROBLEM STATEMENT: A transformer on a utility pole operates at V_p = 8.5 kV on the primary side and supplies electrical energy to a number of nearby houses at V_s = 120 V, both quantities being RMS values. Assume an ideal step-down transformer, a purely resistive load, and a power factor of unity.

(a) What is the turns ratio N_p / N_s of the transformer?

(b) The average rate of energy consumption (or dissipation) in the houses served by the transformer is 78 kW. What are the rms currents in the primary and secondary of the transformer?

(c) What is the resistive load R_s in the secondary circuit? What is the corresponding resistive load R_p in the primary circuit?

- SOLUTION on the next slide

SOLUTION TO SAMPLE PROBLEM 31.08

- (a) The turns ratio is given by $a = N_p / N_s = V_p / V_s$ as we already know (see the third bullet on slide number 6). This leads to a = 8500/120 which works out to be approximately equal to 71. Note that the preferred answer has to be the nearest integer value to the answer actually calculated, since the transformer turns ratio is best specified as an integer value (to the person who would actually be building the whole god-damned thing!).
- (b) Referring back to Figure 1, the average consumed power (also known as dissipated power or rate of energy consumption) is given by $P = V_p I_p \cos\varphi$, where the power P is in watts, and the two RMS voltages are in volts. The power factor, of course, is a unit-less quantity and, in the case under consideration, has already been given as unity.

SOLUTION TO SAMPLE PROBLEM 31.08: CONTD…

Thus we get 78000 = $V_p I_p$ =8500I_p which gives I_p = 9.176 A approximately. We can also write 78000 = $V_s I_s$ =120I_s which gives I_s = 650 A.

As a double-check, make sure that a= I_s / I_p is satisfied (at least, approximately) if you put your calculated values of I_s and I_p in this equation.

©. $R_s = V_s / I_s$ (based on Ohm's law) can be used to calculate R_s. We get R_s = 120/650 ohm = 0.18 ohm (approximately). In a similar manner, $R_p = V_p / I_p$ can be used to calculate R_p. We get R_p = 8500/9.176 ohm approximately = 926 ohm (approximately).

SOLUTION TO SAMPLE PROBLEM 31.08: CONTD…

As a double check on your calculations, make sure that your calculated values approximately satisfy the following equation:

R_p =a*a*R_s

where turns ratio a = N_p/ N_s

TYPES OF CONSTRUCTION

- STEP-DOWN versus STEP-UP
- SINGLE-PHASE versus THREE-PHASE
- SHELL TYPE versus CORE TYPE

CLASSIFICATION BASED ON THE TYPE OF END-USE

1. Power transformer: Used in transmission network, high rating

2. Distribution transformer: Used in distribution network, comparatively lower rating than that of power transformers.

3. Instrument transformer: Used in relay and protection purpose in different instruments in industries, e.g., for extending range of energy-meters

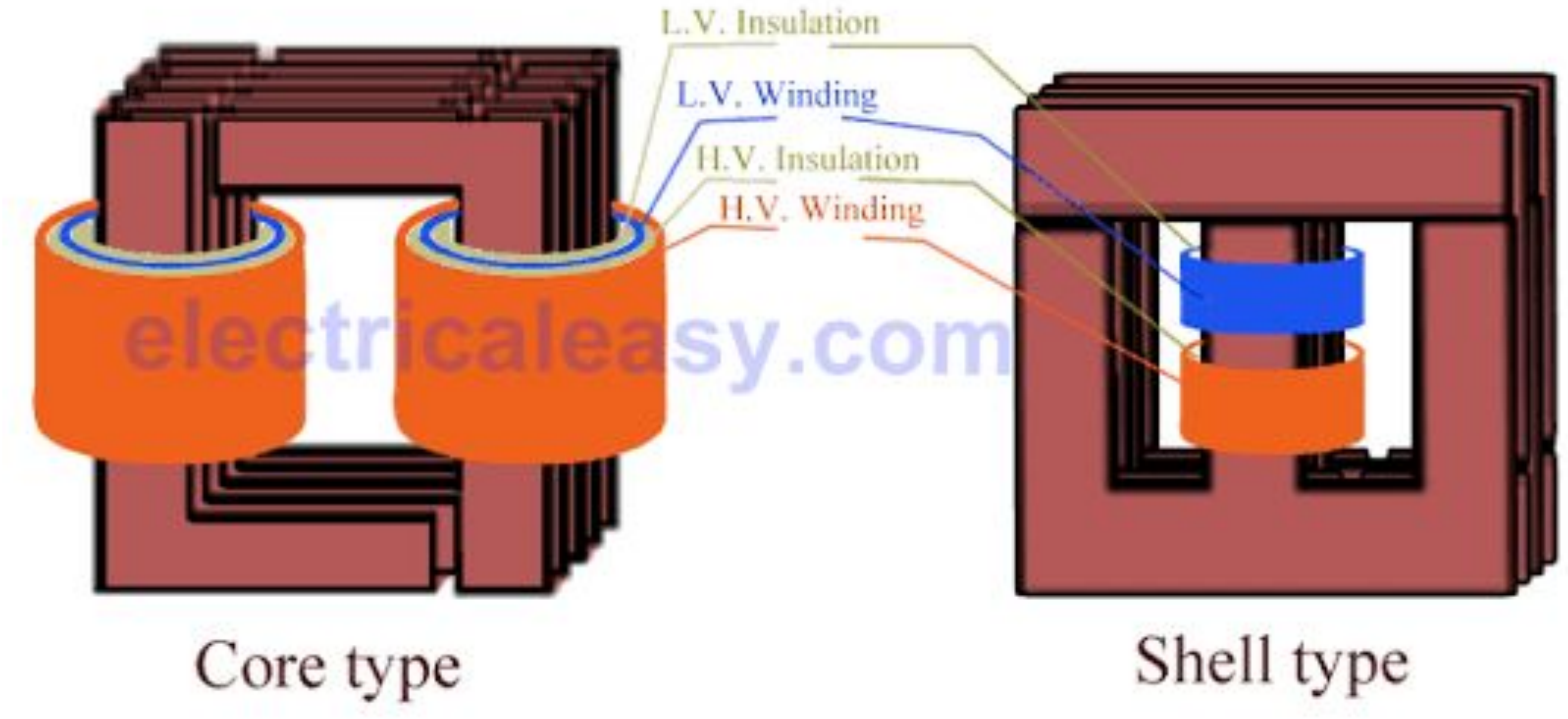
Current transformer (CT)

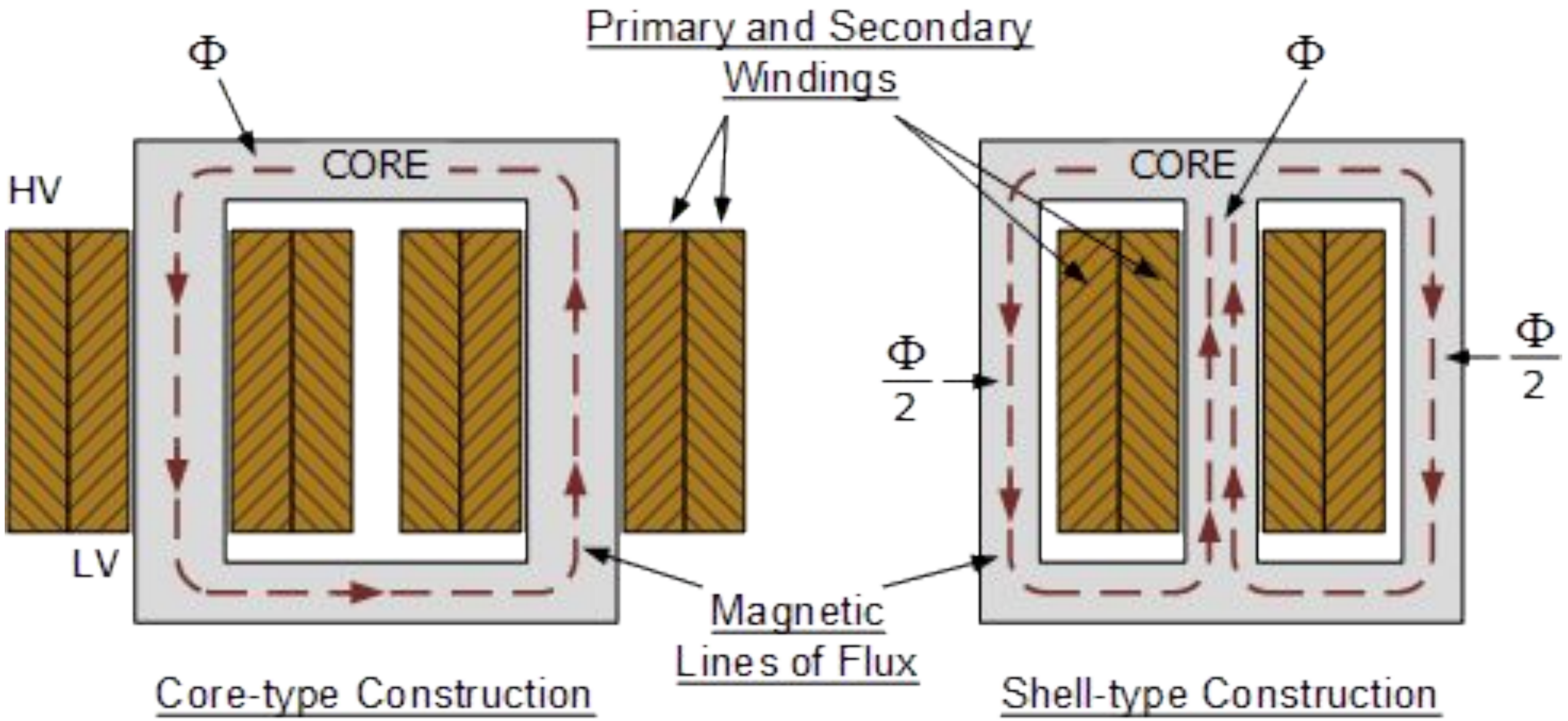
Potential transformer (PT)

CLASSIFICATION BASED ON COOLING TECHNIQUE

1. Oil--filled self cooled type
2. Oil--filled water cooled type
3. Air-blast type (air cooled)
4. Dry type (air cooled)

SHELL TYPE versus CORE TYPE




Primary and Secondary Windings
Φ
CORE
HV
LV
Φ
CORE
Φ/2
Φ/2
Magnetic Lines of Flux
Core-type Construction
Shell-type Construction

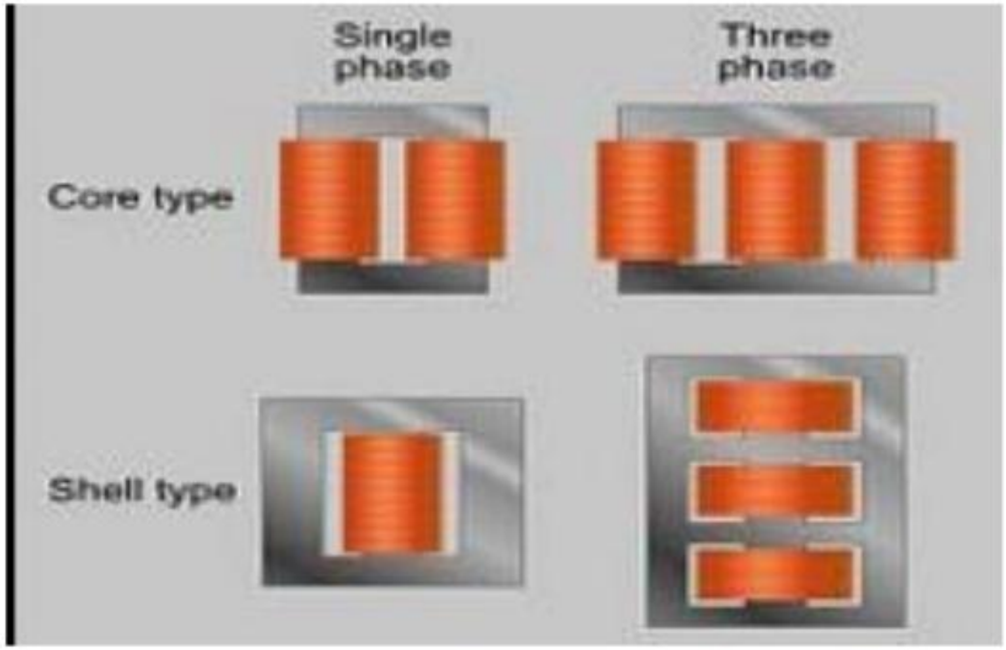
i) Core type transformer

In core type transformer , windings are cylindrical former wound, mounted on the core limbs. The cylindrical coils have different layers and each layer is insulated from each other . Materials like paper , cloth or mica can be used for insulation. Low voltage windings are placed nearer to the core, as they are easier to insulate.

(ii) Shell type transformer

The coils are former wound and mounted in layers stacked with insulation between them. A shell type transformer may have simple rectangular form, or it may have a distributed form

CORE TYPE AND SHELL YYPE CONSTRUCTION



EMF AND VOLTAGE EQUATIONS

- Ep= 4.44BAfNp
- Es=4.44BAfNs

Ep is primary emf, Es is secondary emf, B is the magnetic flux density in core of the transformer (Wb/meter-squared or Tesla), A is the area of cross-section of the core (meter squared), f is the frequency of operation (in c/s or Hz), Np is the number of turns in the primary winding, and Ns is the number of turns in the senondary winding.

Vp=Ep – Ip*Rp if we ignore iron losses completely

Vs=Es-Is*Rs

LOSSES IN TRANSFORMERS

In any electrical machine, ' loss' can be defined as the difference between input power and output power . An electrical transformer is an static device, hence mechanical losses (like windage or friction losses) are absent in it. A transformer only consists of electrical losses (iron losses and copper losses). Transformer losses aresimilar to losses in a DC machine, except that transformers do not have mechanical losses.

CORE LOSSES OR IRON LOSSES

Eddy current loss and hysteresis loss depend upon the magnetic properties of the material used for the construction of core. Hence these losses are also known as core losses or iron losses.

a. Hysteresis loss in transformer:

Hysteresis loss is due to reversal of magnetization in the transformer core. This loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density . It can be given by , Steinmetz formula:

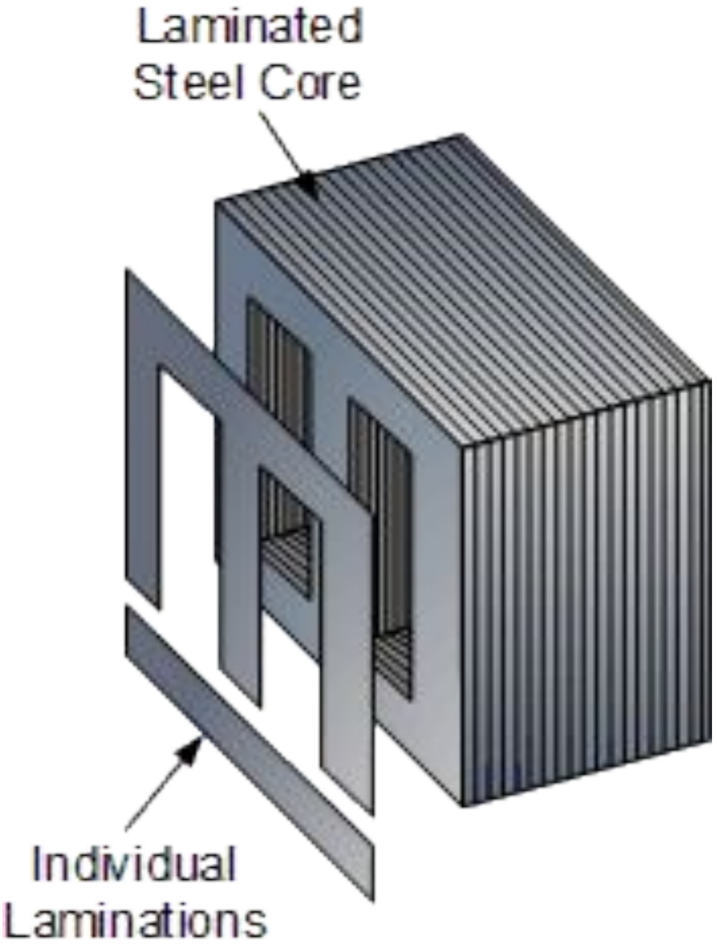
W = ηB fV (watts)

where, η = Steinmetz hysteresis constant, B is the magnetic flux density in core in Wb/meter-squared (Tesla), f is frequency of operation in Hz, and V = volume of the core in meter-cubed

b. Eddy current loss in transformer:

In transformer , AC current is supplied to the primary winding which sets up alternating magnetizing flux. When this flux links with secondary winding, it produces induced emf in it. But some part of this flux also gets linked with other conducting parts like steel core or iron body or the transformer , which will result in induced emf in those parts, causing small circulating current in them. This current is called as eddy current. Due to these eddy currents, some energy will be dissipated in the form of heat.

Laminated Construction of the magnetic core helps in reducing the eddy-current loss



Copper Loss

iCopper loss in transformer

Copper loss is due to ohmic resistance of the transformer windings. Copper loss for the primary winding is Ip*Ip* Rp and for secondary winding is Is*Is* Rs . where, Ip and Is are currents in primary and secondary windings, respectively , Rp and Rs are the resistances of primary and secondary windings, respectively .

It is clear that Cu loss is proportional to square of the current, and current depends on the load. Hence copper loss in transformer varies with the load.

TRANSFORMER EFFICIENCY

Just like any other electrical machine, efficiency of a transformer can be defined as the output power divided by the input power . That is efficiency = output / input .

Transformers are the most highly efficient electrical devices. Most of the transformers have full load efficiency between 95% to 98.5% . As a transformer is highly efficient, output and input are having nearly same value, and hence it is impractical to measure the efficiency of transformer by using output / input ratio. A better method to find efficiency of a transformer is using, efficiency = (input - - losses) / input = 1 -- (losses / input).

All-Day Efficiency

Ordinary or commercial efficiency of a transformer can be given as output power/input power.

But in some types of transformers, their performance can not be judged by this efficiency . For example, distribution transformers have their primaries energized all the time. But, their secondaries supply little load all most of the time during day (as residential use of electricity is observed mostly during evening till midnight). That is, when secondaries of transformer are not supplying any load (or supplying only little load), then only core losses of transformer are considerable and copper losses are absent (or very little). Copper losses are considerable only when transformers are loaded. Thus, for such transformers copper losses are relatively less important. The performance of such transformers is compared on the basis of energy consumed in one day .

All-day efficiency = output energy in KWh over a 24-hour period divided by input energy in KWh over the same 24-hour period.

- All day efficiency of a transformer is always less than ordinary efficiency of it.

VOLTAGE REGULATION

100x(noload secondary voltage-fullload secondary voltage)/fullload secondary voltage

CURRENT CARRYING CAPACITY OF WIRES

- American **Wire Gauge** (**AWG**) is a system of numerical **wire sizes** that start with the lowest numbers (6/0) for the largest **sizes**. The **gauge sizes** are each 26% apart based on the cross sectional area. **AWG** is also known as Brown & Sharpe Gage.**SWG** = Standard or Sterling **Wire Gauge**, a British **wire** measurement system.

Table 1: American Wire Gauge (AWG) Cable / Conductor Sizes and Properties

AWG	Diameter [inches]	Diameter [mm]	Area [mm^2]	Resistance [Ohms / 1000 ft]	Resistance [Ohms / km]	Max Current [Amperes]	Max Frequency for 100% skin depth
0000 (4/0)	0.46	11.684	107	0.049	0.16072	302	125 Hz
000 (3/0)	0.4096	10.40384	85	0.0618	0.202704	239	160 Hz
00 (2/0)	0.3648	9.26592	67.4	0.0779	0.255512	190	200 Hz
0 (1/0)	0.3249	8.25246	53.5	0.0983	0.322424	150	250 Hz
1	0.2893	7.34822	42.4	0.1239	0.406392	119	325 Hz
2	0.2576	6.54304	33.6	0.1563	0.512664	94	410 Hz
3	0.2294	5.82676	26.7	0.197	0.64616	75	500 Hz
4	0.2043	5.18922	21.2	0.2485	0.81508	60	650 Hz
5	0.1819	4.62026	16.8	0.3133	1.027624	47	810 Hz
6	0.162	4.1148	13.3	0.3951	1.295928	37	1100 Hz
7	0.1443	3.66522	10.5	0.4982	1.634096	30	1300 Hz
8	0.1285	3.2639	8.37	0.6282	2.060496	24	1650 Hz
9	0.1144	2.90576	6.63	0.7921	2.598088	19	2050 Hz
10	0.1019	2.58826	5.26	0.9989	3.276392	15	2600 Hz
11	0.0907	2.30378	4.17	1.26	4.1328	12	3200 Hz
12	0.0808	2.05232	3.31	1.588	5.20864	9.3	4150 Hz
13	0.072	1.8288	2.62	2.003	6.56984	7.4	5300 Hz
14	0.0641	1.62814	2.08	2.525	8.282	5.9	6700 Hz
15	0.0571	1.45034	1.65	3.184	10.44352	4.7	8250 Hz
16	0.0508	1.29032	1.31	4.016	13.17248	3.7	11 k Hz
17	0.0453	1.15062	1.04	5.064	16.60992	2.9	13 k Hz
18	0.0403	1.02362	0.823	6.385	20.9428	2.3	17 kHz
19	0.0359	0.91186	0.653	8.051	26.40728	1.8	21 kHz
20	0.032	0.8128	0.518	10.15	33.292	1.5	27 kHz
21	0.0285	0.7239	0.41	12.8	41.984	1.2	33 kHz
22	0.0254	0.64516	0.326	16.14	52.9392	0.92	42 kHz
23	0.0226	0.57404	0.258	20.36	66.7808	0.729	53 kHz
24	0.0201	0.51054	0.205	25.67	84.1976	0.577	68 kHz
25	0.0179	0.45466	0.162	32.37	106.1736	0.457	85 kHz
26	0.0159	0.40386	0.129	40.81	133.8568	0.361	107 kHz
27	0.0142	0.36068	0.102	51.47	168.8216	0.288	130 kHz
28	0.0126	0.32004	0.081	64.9	212.872	0.226	170 kHz
29	0.0113	0.28702	0.0642	81.83	268.4024	0.182	210 kHz
30	0.01	0.254	0.0509	103.2	338.496	0.142	270 kHz
31	0.0089	0.22606	0.0404	130.1	426.728	0.113	340 kHz
32	0.008	0.2032	0.032	164.1	538.248	0.091	430 kHz
33	0.0071	0.18034	0.0254	206.9	678.632	0.072	540 kHz
34	0.0063	0.16002	0.0201	260.9	855.752	0.056	690 kHz
35	0.0056	0.14224	0.016	329	1079.12	0.044	870 kHz
36	0.005	0.127	0.0127	414.8	1360	0.035	1100 kHz
37	0.0045	0.1143	0.01	523.1	1715	0.0289	1350 kHz
38	0.004	0.1016	0.00797	659.6	2163	0.0228	1750 kHz
39	0.0035	0.0889	0.00632	831.8	2728	0.0175	2250 kHz
40	0.0031	0.07874	0.00501	1049	3440	0.0137	2900 kHz