Transformers (3)

Transformer Efficiency

The intensity of power loss in a transformer determines its efficiency. The efficiency of a transformer is reflected in power (wattage) loss between the primary (input) and secondary (output) windings. Then the resulting efficiency of a transformer is equal to the ratio of the power output of the secondary winding to the power input of the primary winding. It is typically high.

We can express efficiency as:

$$\text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}} \tag{1}$$

We can write this as:

$$\text{Efficiency} = \frac{\text{Output Power}}{\text{Ouput Power + Losses}} \tag{2}$$

or

$$\text{Efficiency} = \frac{\text{Input Power-Losses}}{\text{Input Power}} \tag{3}$$

Considering the final equivalent circuit (Figure 1) we can write:

$$\text{Efficiency}=\frac{V_1 I_1 \times PF}{V_1 I_1 \times PF + P_{iron} + I_1^2 R_{1eq}} \tag{4}$$

Where PF is the power factor and P_{iron} = Iron Loss.

Rearranging (4) by dividing by I_1 gives:

$$\text{Efficiency}=\frac{V_1 \times PF}{V_1 \times PF + \frac{P_{iron}}{I_1} + I_1 R_{1eq}} \tag{5}$$

The Maximum Efficiency is when Efficiency, given by equation (5) is equal to 1, so:

$$\frac{P_{iron}}{I_1} = I_1 R_{1eq} \tag{6}$$

So:

$$P_{iron} = I_1^2 R_{1eq} = \text{Copper Losses} \tag{7}$$

Hence, for maximum efficiency the iron losses and the copper losses must be equal.

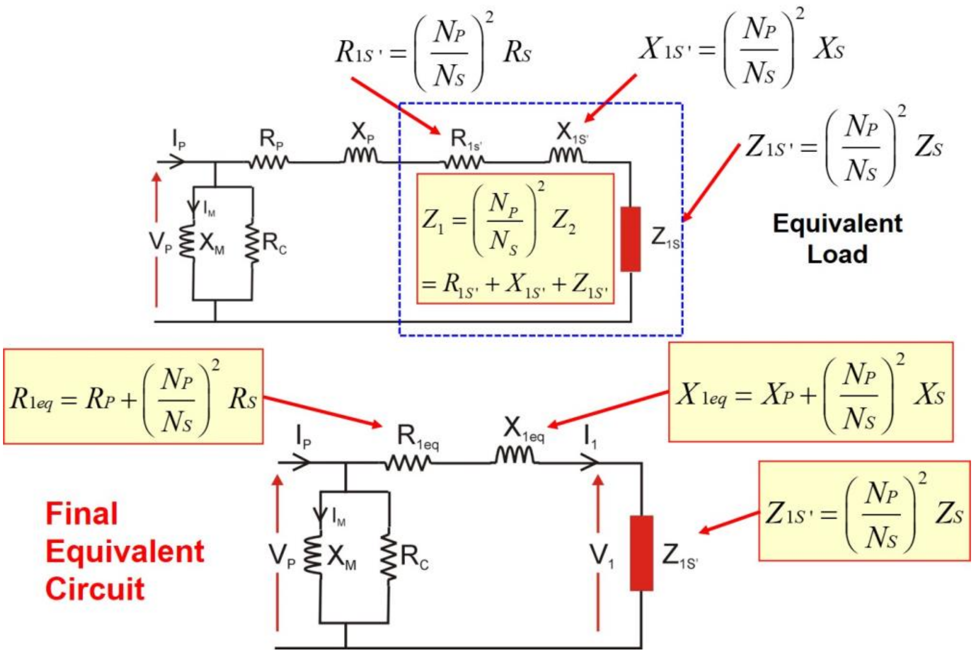

Figure 1. Equivalent Circuit of Single-Phase Transformer

Voltage Regulation

Transformer voltage regulation is the ratio, or percentage value, by which a transformers output terminal voltage varies, either up or down, from its no-load value because of variations in the connected load current. We have seen that when the primary winding of a transformer is energised, it produces a secondary voltage and current at an amount determined by the transformers turns ratio. So, if a single-phase transformer has a step down turns ratio of 2:1 and 240V is applied to the high voltage primary winding, we would expect to see an output terminal voltage on the secondary winding of 120 V, because we have assumed it to be an ideal transformer. However, all transformers suffer from losses consisting of I^2R copper losses and magnetic core losses which would reduce this ideal secondary value by a few percent.

When there is no-load connected to the transformers secondary winding, that is its output terminals are open-circuited, there is no closed-loop condition, so there is no output load current ($I_L = 0$) and the transformer no-load secondary voltage is a result of the fixed primary voltage and the turns ratio of the transformer. Loading the secondary winding with a load impedance causes a secondary current to flow through the internal winding of the transformer. Thus, voltage drops due to the windings internal resistance and its leakage reactance causing the output terminal voltage to change. This is depicted in Figure 2.

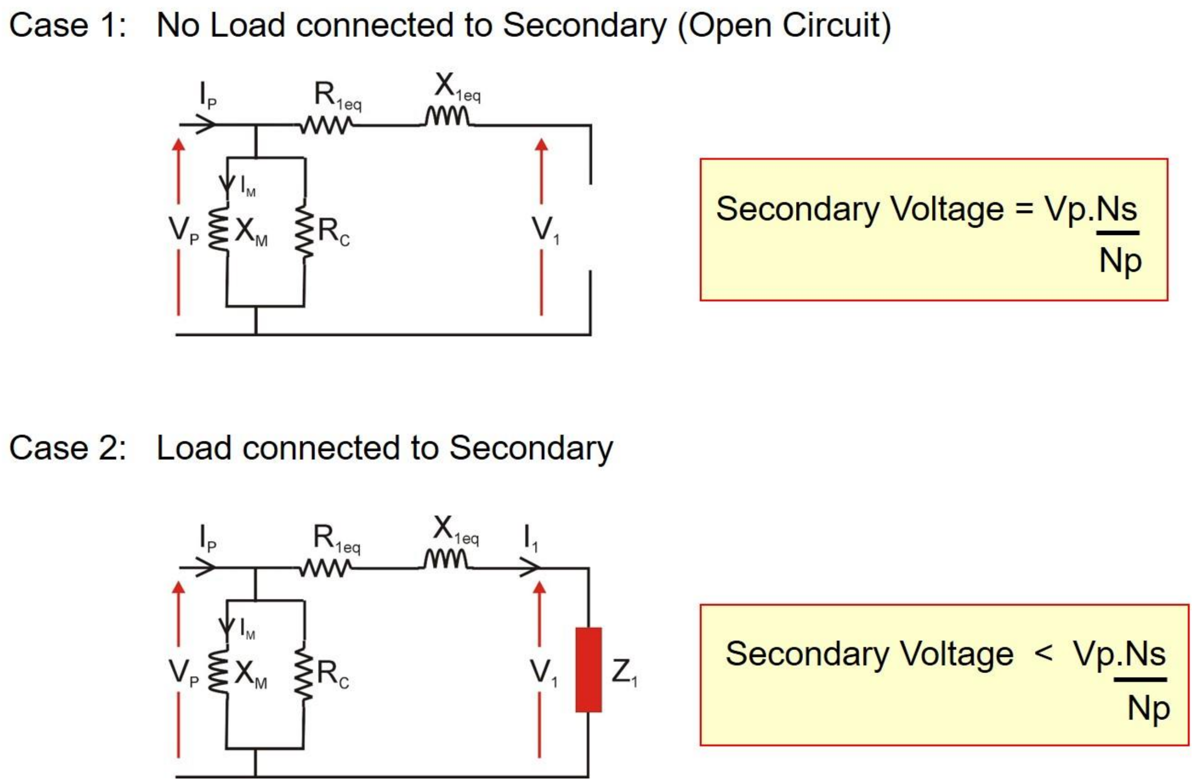

Figure 2. Secondary voltage under open circuit and load conditions

The largest drop in the secondary voltage will be under full load conditions, as shown in Figure 3. We can calculate the voltage regulation from:

$$\text{Voltage Regulation (\%)} = \frac{V_{soc} - Vs}{V_{soc}} \times 100\% \qquad (8)$$

Where, V_s is the secondary voltage under load and V_{soc} is the secondary voltage under open circuit, or no load, condition.

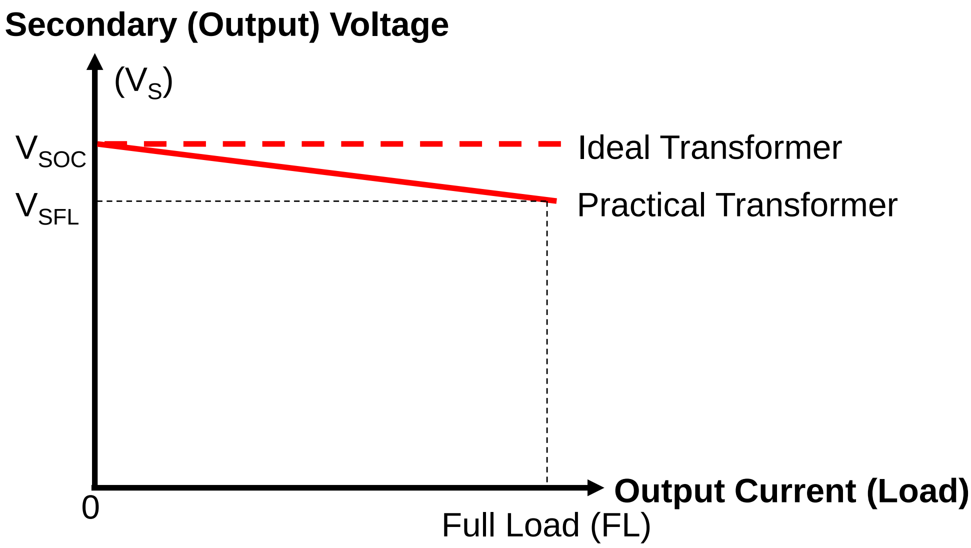

Figure 3. Drop in output voltage with increasing load.

Bibliography

1. Theodore Wildi "Electrical Machines, Drives, and Power Systems" 2nd Edition, Prentice-Hall (1981). Chapter 10.
2. Edward Hughes "Electrical Technology" 10th Edition, Pearson Education Limited (2008). Chapter 34.