Voltage regulation and efficiency

Since a real transformer contains series impedances, the transformer's output voltage varies with the load even if the input voltage is constant. To compare transformers in this respect, the quantity called a full-load voltage regulation (VR) is defined as follows:

$$VR = \frac{V_{s,nl} - V_{s,fl}}{V_{s,fl}} \cdot 100\% = \frac{V_p / a - V_{s,fl}}{V_{s,fl}} \cdot 100\% \qquad (4.52.1)$$

In a per-unit system:

$$\boxed{VR = \frac{V_{p,pu} - V_{s,fl,pu}}{V_{s,fl,pu}} \cdot 100\%} \qquad (4.52.2)$$

Where $V_{s,nl}$ and $V_{s,fl}$ are the secondary no load and full load voltages.

Note, the VR of an ideal transformer is zero.

The transformer phasor diagram

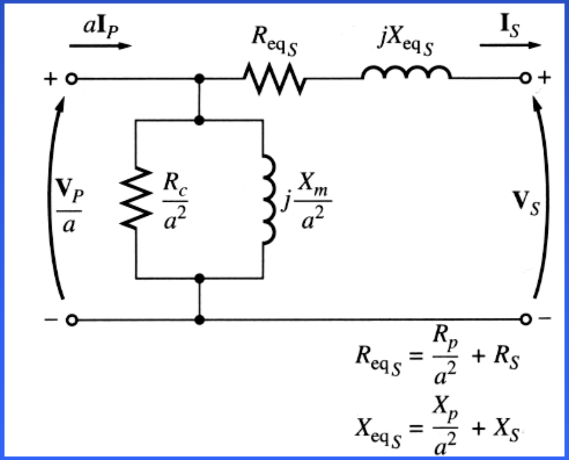
To determine the VR of a transformer, it is necessary to understand the voltage drops within it. Usually, the effects of the excitation branch on transformer VR can be ignored and, therefore, only the series impedances need to be considered. The VR depends on the magnitude of the impedances and on the current phase angle.

A phasor diagram is often used in the VR determinations. The phasor voltage V_s is assumed to be at 0^0 and all other voltages and currents are compared to it.

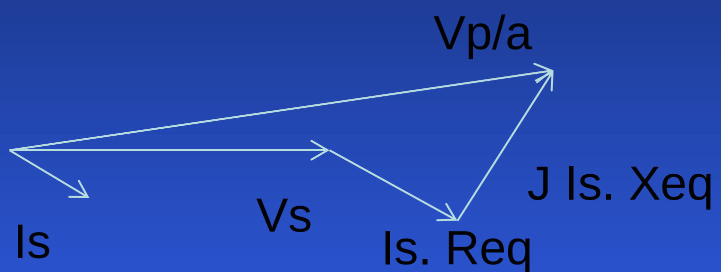
Considering the diagram and by applying the Kirchhoff's voltage law, the primary voltage is:

$$\frac{V_p}{a} = V_s + R_{eq} I_s + jX_{eq} I_s \qquad (4.53.1)$$

A transformer phasor diagram is a graphical representation of this equation.



Phasor Diagram

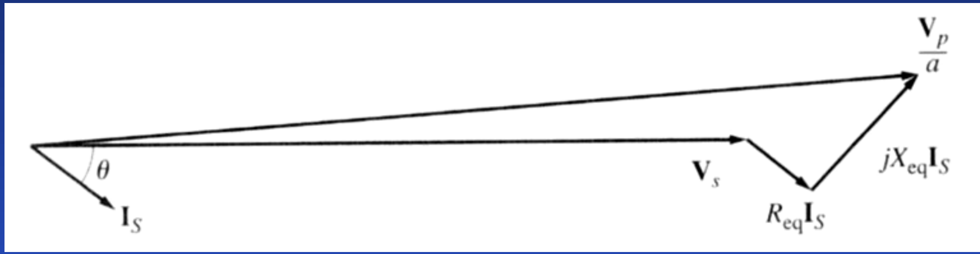


$$\frac{V_p}{a} = V_s + R_{eq} I_s + jX_{eq} I_s$$

The transformer phasor diagram

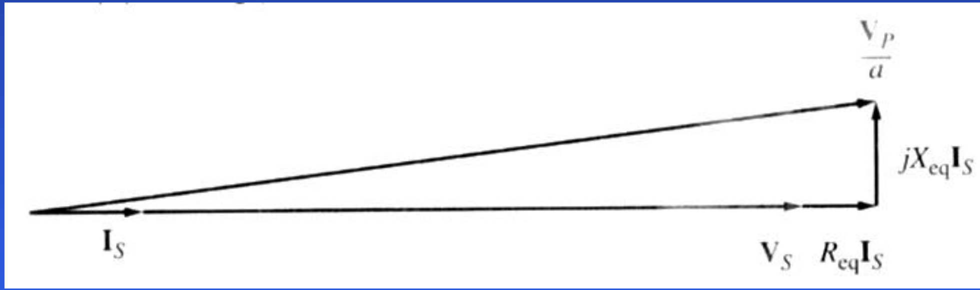
A transformer operating at a lagging power factor:

It is seen that $V_p/a > V_s$, VR > 0



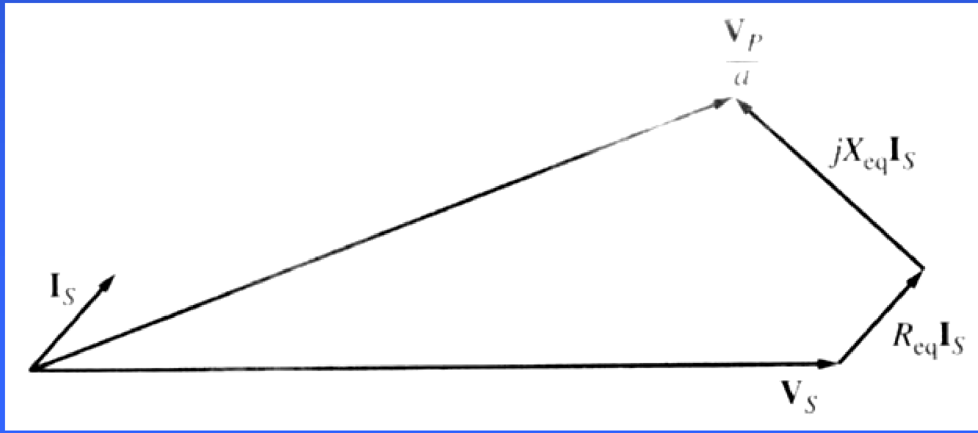
A transformer operating at a unity power factor:

It is seen that $VR > 0$

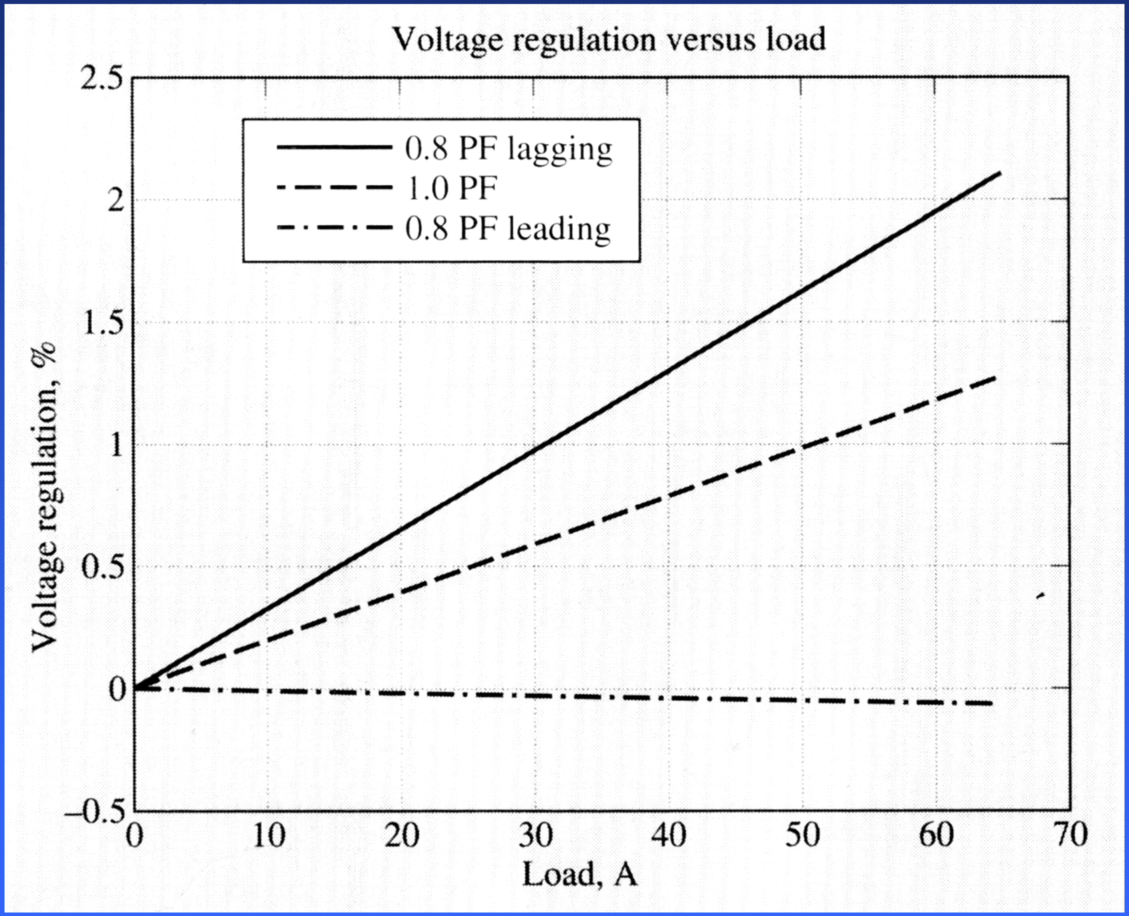


A transformer operating at a leading power factor:

If the secondary current is leading, the secondary voltage can be higher than the referred primary voltage; VR < 0.



The transformer VR



The transformer efficiency

The efficiency of a transformer is defined as:

$$\boxed{\eta = \frac{P_{out}}{P_{in}} \cdot 100\% = \frac{P_{out}}{P_{out} + P_{loss}} \cdot 100\%} \quad (4.55.1)$$

Note: the same equation describes the efficiency of motors and generators.

Considering the transformer equivalent circuit, we notice three types of losses:

1. Copper (I^2R) losses – are accounted for by the series resistance
2. Hysteresis losses – are accounted for by the resistor R_c.
3. Eddy current losses – are accounted for by the resistor R_c.

Since the output power is

$$P_{out} = V_s I_s \cos\theta_s \quad (4.55.2)$$

The transformer efficiency is

$$\boxed{\eta = \frac{V_s I_s \cos\theta}{P_{Cu} + P_{core} + V_s I_s \cos\theta} \cdot 100\%} \quad (4.55.3)$$

The transformer efficiency

The copper losses are:

$$P_{Cu} = I_S^2 R_{eq}$$

The core losses are:

$$P_{core} = \frac{\left(V_p / a\right)^2}{R_C}$$

The output power of the transformer at the given Power Factor is:

$$P_{out} = V_S I_S \cos\theta$$

Therefore, the efficiency of the transformer is

$$\eta = \frac{P_{out}}{P_{Cu} + P_{core} + P_{out}} \cdot 100\%$$

Example 2.5