Regulation of the transformer:

The voltage regulation of the transformer is **the percentage change in the output voltage from no-load to full-load**. And since power factor is a determining factor in the secondary voltage, power factor influences voltage regulation. This means the voltage regulation of a transformer is a dynamic, load-dependent number.

Transformer's voltage regulation is the ratio of the difference between transformer no load and full load output voltage to its full load output voltage expressed as a percentage (%).

In other words, transformer voltage regulation is the measure of supplying constant output voltage with different load currents.

In simple words, the change in magnitude of input and output voltage of the transformer is know as voltage regulation. i.e. the change in transformer secondary terminal voltage from no load to full load related to the no load voltage is known as "voltage regulation".

Mathematically, the voltage regulation is expressed by the following formula.

$$\text{Voltage Regulation} = \frac{E_{\text{No Load}} - V_{\text{Full Load}}}{V_{\text{Full Load}}}$$

$$\%\ \text{Voltage Regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

Voltage regulation for primary winding of the transformer

$$\%\ \text{Voltage Regulation} = \frac{E_1 - V_1}{E_1} \times 100$$

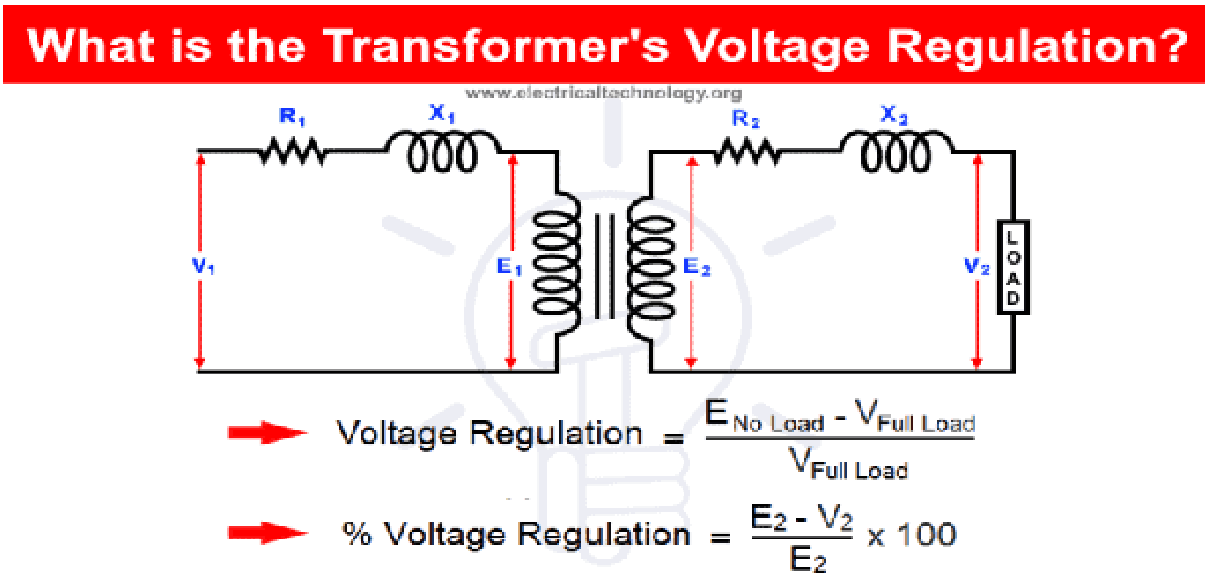
Where:

- E_1 = No load primary terminal voltage
- V_1 = Full load primary terminal voltage
- E_2 = No load secondary terminal voltage
- V_2 = Full load secondary terminal voltage

A Transformer will generally provide a higher output voltage at no load than when the transformer is fully loaded according to the transformer nameplate data rating capacity. Stated differently, under load, a transformer's output voltage drops slightly.

Power transformer should provide a constant output voltage (ideally as it is not possible in real). So it is the better option to have as much as little variation in output voltage with different load currents. In this scenario, voltage regulation shows that how much a transformer can provide a constant secondary voltage with different loads connected to the transformer output.

The following basic transformer circuit and solved example will clear the concept of transformer's voltage regulation.



In first scenario, Suppose there is no load connected to the transformer's secondary, In this case of open circuit:

- No load current is flowing due to open circuit.
- When no load current flows, there is no voltage drop and reactive drops across resistor and inductors respectably.
- Voltage drops across primary terminals are negligible.

In second scenario, the transformer is loaded i.e. there is a load connected to the secondary terminals of the transformer. In this case of loaded circuit:

- Load current is flowing due to completed circuit and load connected to the secondary terminals.
- Load current flows through the load, so there must be voltage drops across resistors and inductors.
- This way, the average value of voltage regulation is more than that of transformer at no load.

For better performance, voltage regulation should be low (ideal zero), i.e. the higher the voltage regulation, the worst of the transformer's efficiency and performance will be.

The above circuit and explanation, following two points are concluded:

- In a transformer, the value of primary voltage is always greater than the induced EMF in the primary windings.

$$\mathbf{V_1 > E_1}$$

- In a transformer, the value of secondary terminal voltage at no load is always greater than the secondary terminal voltage at full load.

$E_2 > V_2$

Based on the above information from the mentioned circuit diagram, the following two equations can be made:

- $V_1 = I_1R_1 \, Cos\theta_1 + I_1X_1 \, Sin\theta_1 + E_1$
- $E_2 = I_2R_2 \, Cos\theta_2 + I_2X_2 \, Sin\theta_2 + V_2$

For various kind of loads i.e. inductive and capacitive loads etc, the following expression at no load secondary voltage.

Voltage Regulation for Inductive Loads (Lagging Power Factor)

$$E_2 = I_2R_{02} \, Cos\theta_2 + I_2X_{02} \, Sin\theta_2 + V_2$$

$$E_2 – V_2 = I_2R_{02} \, Cos\theta_2 + I_2X_{02} \, Sin\theta_2$$

Transformer’s voltage regulation at lagging power factor (Inductive Load):

$$\frac{E_2 - V_2}{E_2} \times 100 = \frac{I_2R_{02}}{E_2} \times 100 \, Cos\theta_2 + \frac{I_2X_{02}}{E_2} \times 100 \, Sin\theta_2$$

Voltage Regulation for Capacitive Loads (Leading Power Factor)

$$E_2 = I_2R_{02} \, Cos\theta_2 – I_2X_{02} \, Sin\theta_2 + V_2$$

$$E_2 – V_2 = I_2R_{02} \, Cos\theta_2 – I_2X_{02} \, Sin\theta_2$$

Transformer’s voltage regulation at leading power factor (Capacitive Load):

$$\frac{E_2 - V_2}{E_2} \times 100 = \frac{I_2R_{02}}{E_2} \times 100 \, Cos\theta_2 - \frac{I_2X_{02}}{E_2} \times 100 \, Sin\theta_2$$

Where:

- $(I_2R_{02} / E_2) \times 100$ is a percentage resistance drop
- $(I_2X_{02} / E_2) \times 100$ is a percentage reactance drop

Examples of Voltage Regulation

Example 1:

Suppose a transformer has a no load voltage of 240 volts and a full load voltage of 230 volts. The transformer's Regulation is calculated as follows.

% Voltage Regulation = [{(No Load Voltage – Full Load Voltage) / Full Load voltage} x 100]

% Voltage Regulation = [{(240V – 230V) / 230} x 100]

% Voltage Regulation = 4.347%

Example 2:

A 50kVA transformer has 200 turns and 40 turns on the primary and secondary windings respectively. Resistance on primary and secondary are 0.15 Ω and 0.005 Ω respectively. The value of leakage reactances on primary and secondary windings are 0.55 and 0.0175 Ω respectively. If the supply voltage on the primary side is 1100V, Calculate:

1. Equivalent impedance transferred to Primary Windings
2. Secondary terminal Voltage at Full load having a lagging power factor of 0.8.
3. Voltage regulation

Solution:

Given Data:

- Primary Voltage: 1100V
- Primary Turns: 200
- Secondary Turns: 40
- $R_1 = 0.15\ \Omega$
- $R_2 = 0.005\ \Omega$
- $X_1 = 0.55\ \Omega$
- $X_2 = 0.0175\ \Omega$
- Power Factor = Cos θ = 0.8 Lagging

(1)

Turn ratio = $K = N_2 / N_1 = 40 / 200 =$ **1/5**

$R_{01} = R_1 + R_2 / K^2 = 0.15\Omega + 0.005\Omega / (1/5)^2 = 0.275\ \Omega$

$X_{01} = X_1 + X_2 / K^2 = 0.55\Omega + 0.0175\Omega / (1/5)^2 = 0.987\ \Omega$

$\mathbf{Z_{01} = 0.275 + j\ 0.987 = 1.025\ \angle 74.43^{o}}$

$\mathbf{Z_{02} = K^2 Z_{01} = (1/5)^2\ (0.275 + j\ 0.987) = (0.011 + j\ 0.039)}$

(2)

No-load secondary voltage = $KV_1 = (1/5) \times 1100V =$ **220 V**

Secondary current: $I_2 = 50 \times 10^3 / 220V = 227.27$ A … (I = P/V = 50kVA / 220V)

$\mathbf{I_2 = 227.27\ A}$

Full-load voltage drop as referred to secondary

= I_2 (R_{02} Cos θ + X_{02} Sin θ)

= 227.27 A (0.011 × 0.8 – 0.039 × 0.6) = **– 3.32 V**

Secondary terminal voltage on load = **220V – 3.32V = 216.68 V**

Full Load Secondary Voltage: 216.68 V

(3)

% Regulation = 3.32V × 100/220 = **1.51**

or

Voltage Regulation:

% Voltage Regulation = ($V_{No\ load}$ – $V_{Full\ Load}$ / $V_{Full\ Load}$) x 100

= (220V – 216.68V / 216.68V) x 100 = 1.53

% Voltage Regulation = 1.53

Transformer's Zero Voltage Regulation

Zero voltage regulation means the "no load voltage" and "full load voltage" of the transformer is equal i.e. there is no difference between them. Zero voltage regulation indicates the highest possible performance of a transformer which is only possible in an theoretical and ideal transformer.

Apart the theory, the lower the voltage regulation percentage, the more stable and constant the secondary terminal voltage to the loads with better regulation.

How to Improve the Transformer Regulation?

A device known as **ferroresonant transformer** (a combination of transformer and LC resonant circuit) is used to improve the transformer regulation (i.e. reduce the percentage of voltage regulation of a transformer). The iron core of ferroresonant transformer is full of flux (magnetic lines) for large portion of the AC cycle. This way, the transformer primary current and variation in supply voltage have little effect on the transformer's core magnetic flux density. It means the transformer's secondary terminals output is almost constant voltage without being affected by major variation in the supply voltage to the primary windings of the transformer.