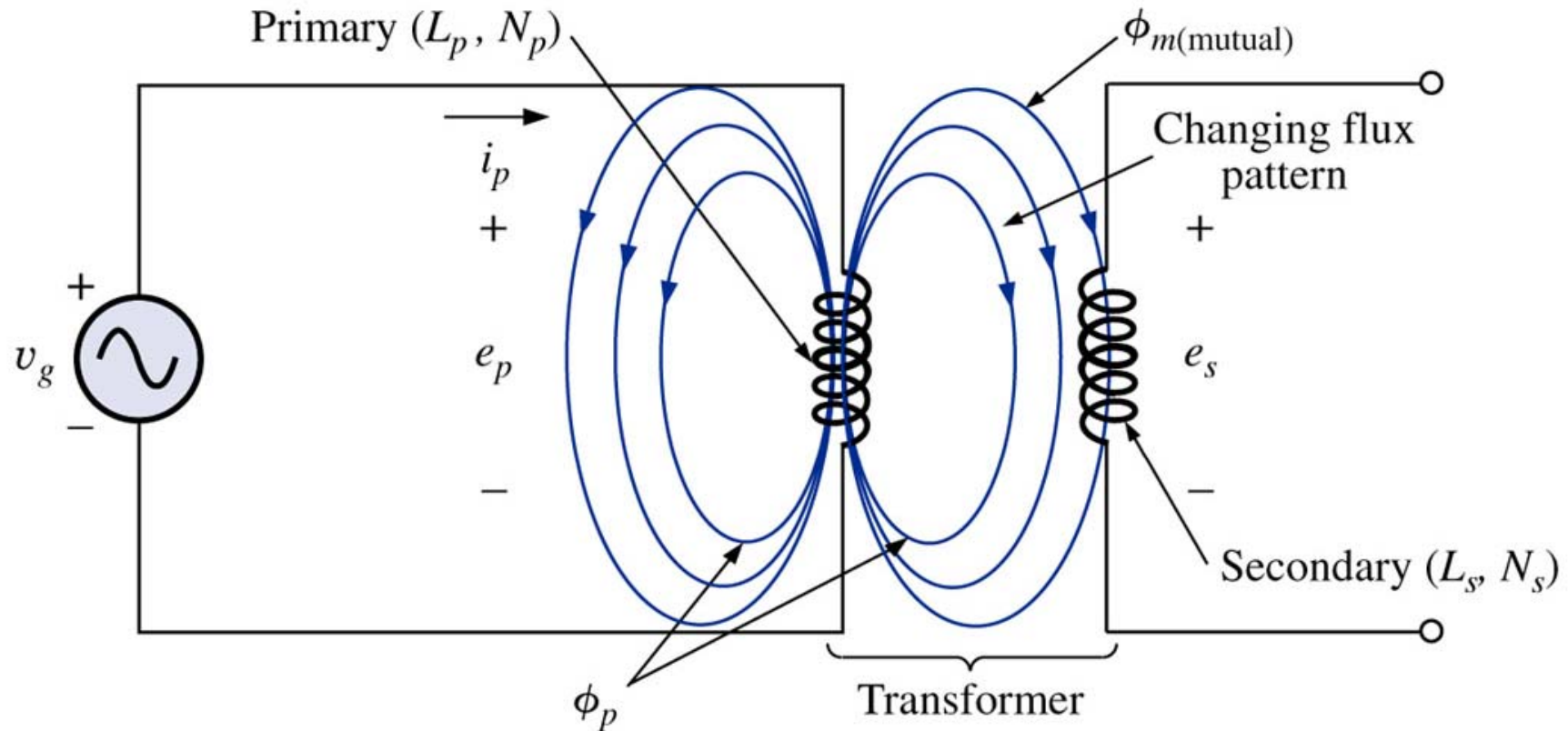


Indutância mútua – fluxo mútuo



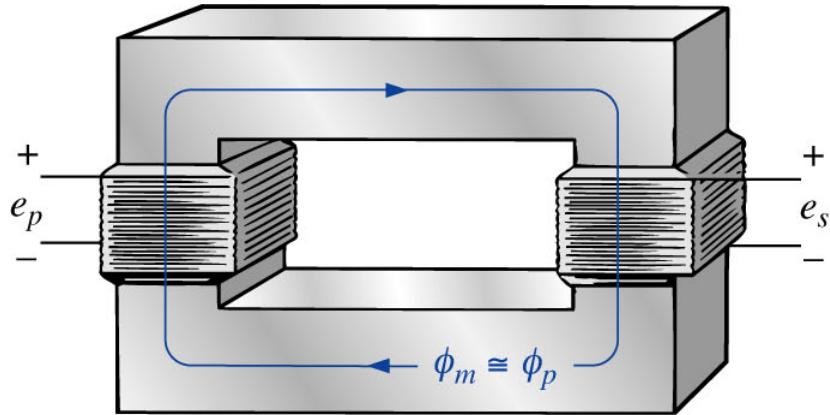
No primário:
$$e_p = N_p \frac{d\phi_p}{dt}$$

$$e_p = L_p \frac{di_p}{dt}$$

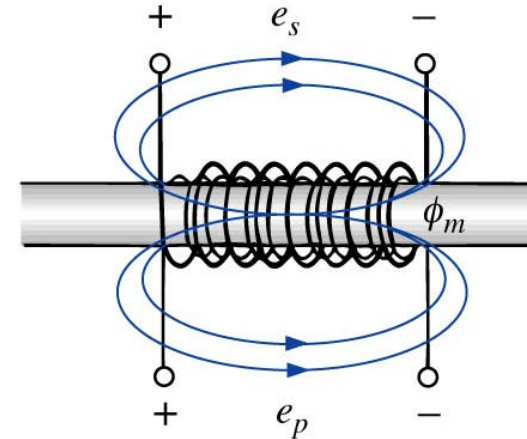
No secundário:
$$e_s = N_s \frac{d\phi_s}{dt}$$

$$e_s = L_s \frac{di_s}{dt}$$

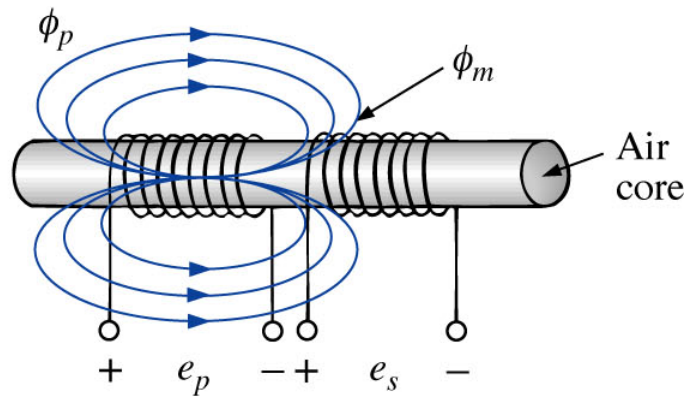
Coeficiente de acoplamento



Steel core
 $k \cong 1$



Any core
 $k \cong 1$



$$k = \frac{\phi_m}{\phi_1} \ll 1 \text{ (0.01} \rightarrow \text{0.3)}$$

$$k = \frac{\phi_m}{\phi_p}$$

Indutância mútua entre dois enrolamentos

$$M = N_s \frac{d\phi_m}{di_p}$$

$$M = N_p \frac{d\phi_p}{di_s}$$

$$M = k \sqrt{L_p \cdot L_s}$$


No primário:

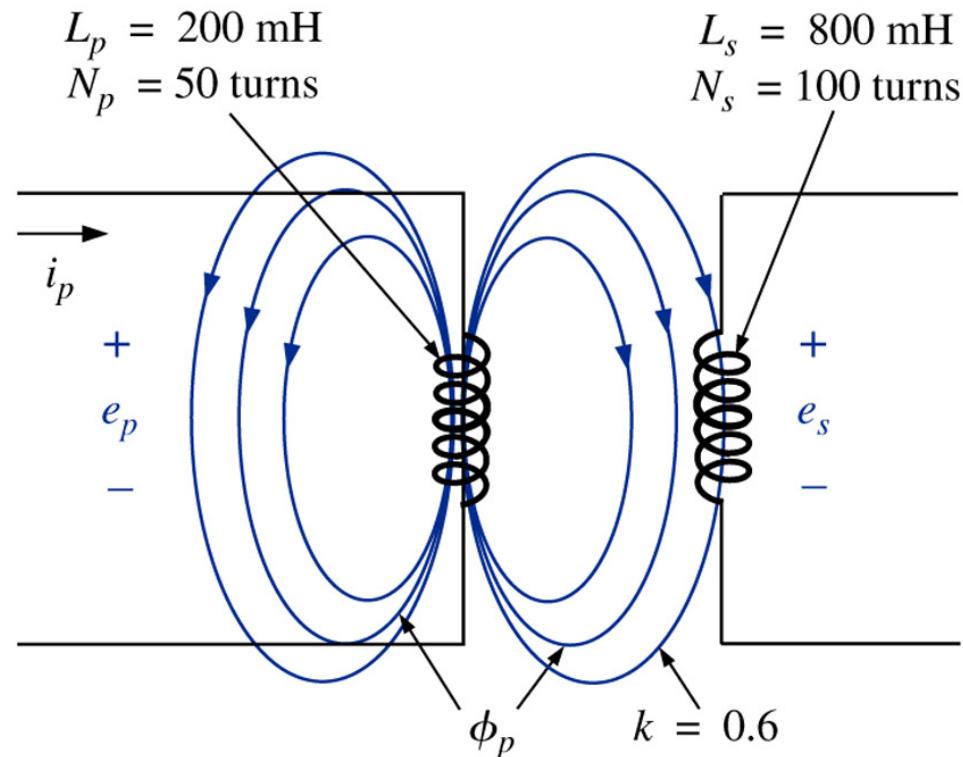
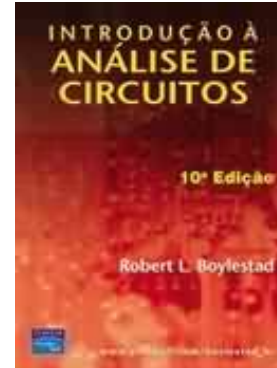
$$e_p = M \frac{di_s}{dt}$$

No secundário:

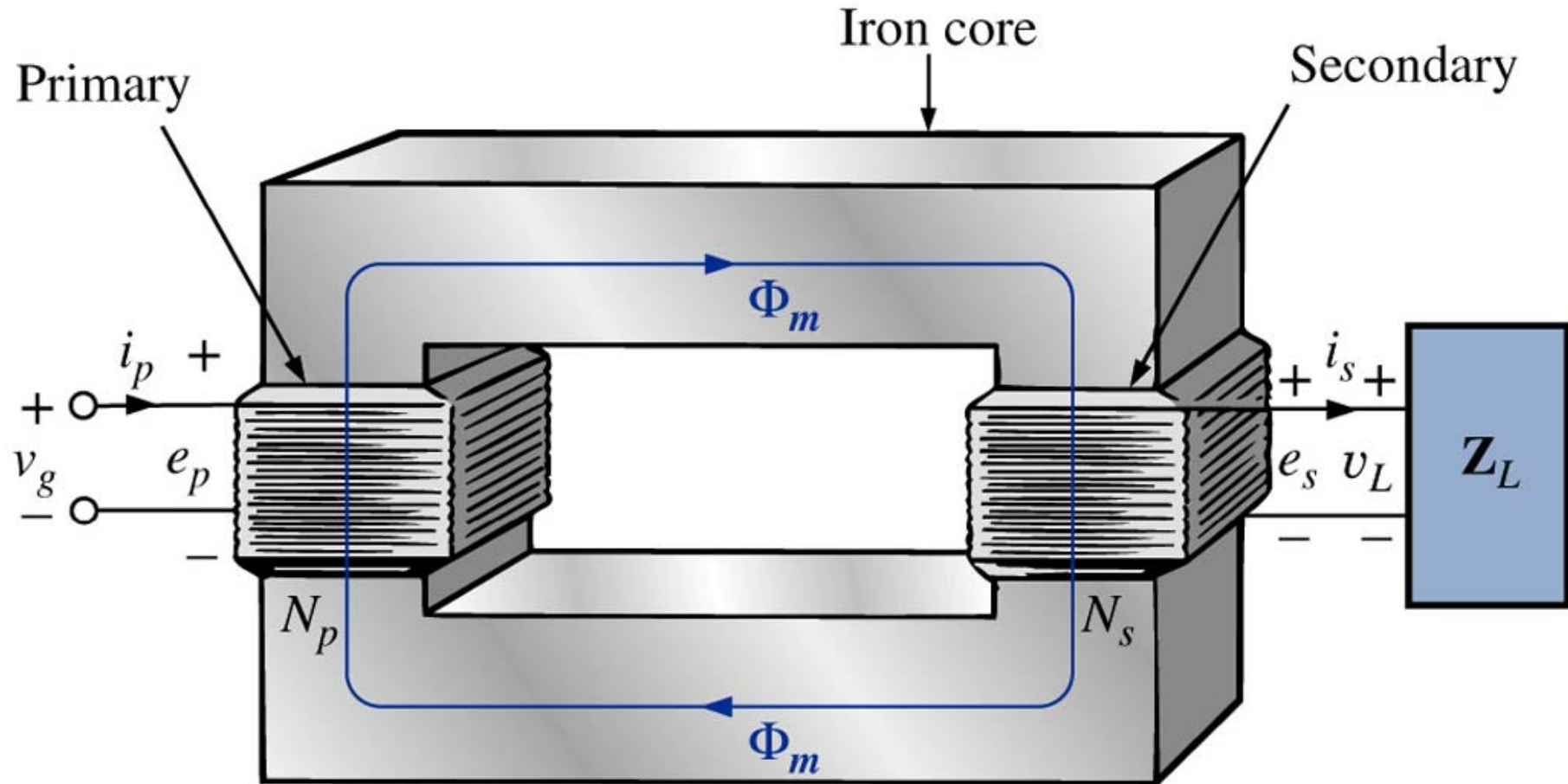
$$e_s = M \frac{di_p}{dt}$$

Indutância mútua entre dois enrolamentos

Exemplo 21.1, pag. 638: 



Transformador com núcleo de ferro



Transformador com núcleo de ferro

Entrada em corrente senoidal:

$$i_p = \sqrt{2} \cdot I_p \cdot \text{sen}(\omega t)$$

$$\phi_m = \Phi_m \cdot \text{sen}(\omega t)$$

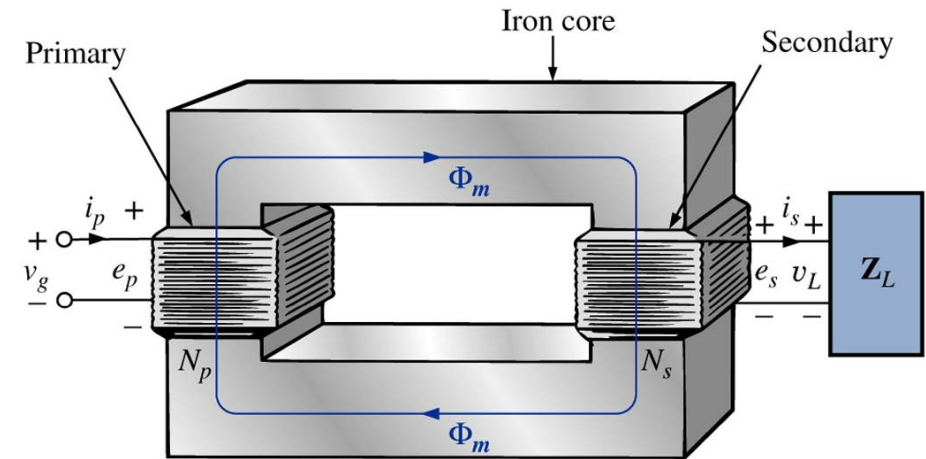
Tensão induzida no primário:

$$e_p = N_p \frac{d\phi_p}{dt} = N_p \frac{d\phi_m}{dt}$$

$$e_p = N_p \frac{d(\Phi_m \cdot \text{sen}(\omega t))}{dt}$$

$$e_p = \omega \cdot N_p \cdot \Phi_m \cdot \cos(\omega t)$$

$$e_p = \omega \cdot N_p \cdot \Phi_m \cdot \text{sen}(\omega t + 90^\circ)$$



Valor eficaz da tensão no primário:

$$E_p = \frac{\omega \cdot N_p \cdot \Phi_m}{\sqrt{2}}$$

$$E_p = 4,44 \cdot f \cdot N_p \cdot \Phi_m$$

Transformador com núcleo de ferro

Valor eficaz da tensão no secundário:

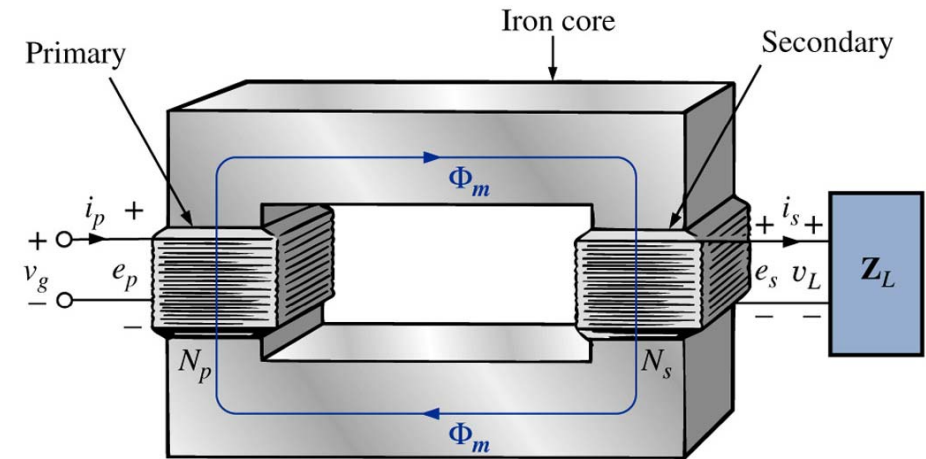
$$E_s = \frac{\omega \cdot N_s \cdot \Phi_m}{\sqrt{2}}$$

$$E_s = 4,44 \cdot f \cdot N_s \cdot \Phi_m$$

Relação entre primário e secundário:

$$\frac{E_p}{E_s} = \frac{4,44 \cdot f \cdot N_p \cdot \Phi_m}{4,44 \cdot f \cdot N_s \cdot \Phi_m}$$

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$



Em termos de valores instantâneos:

$$\frac{e_p}{e_s} = \frac{N_p (d\phi_m / dt)}{N_s (d\phi_m / dt)}$$

$$\frac{e_p}{e_s} = \frac{N_p}{N_s}$$

Transformador com núcleo de ferro

Relação de transformação:

$$a = \frac{N_p}{N_s}$$

Se $a < 1$:

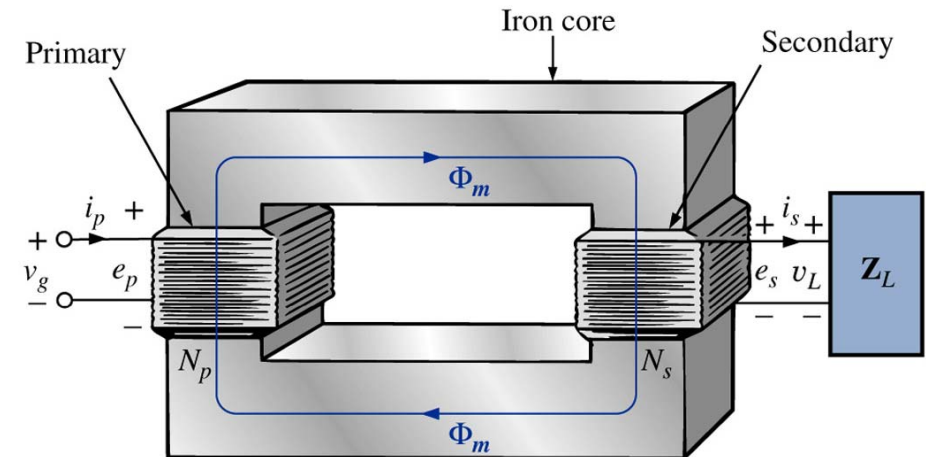
$$a < 1 \rightarrow N_s > N_p$$

Transformador elevador de tensão

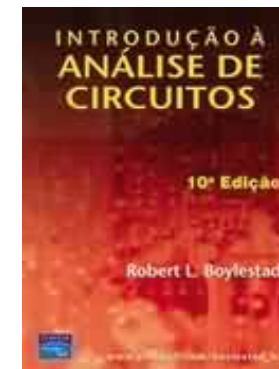
Se $a > 1$:

$$a > 1 \rightarrow N_p > N_s$$

Transformador abaixador de tensão



Exemplo 21.2, pag. 639:



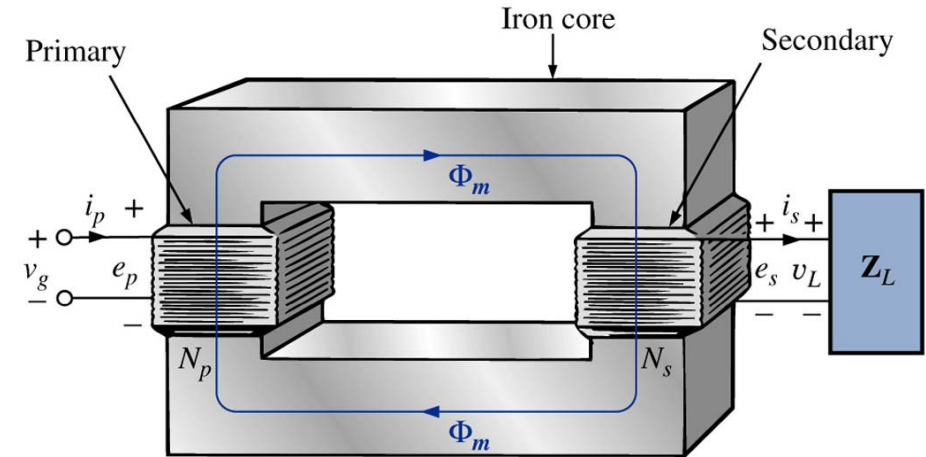
Transformador com núcleo de ferro

Corrente no primário:

$$i_p = i_p' + i_{\phi m} \quad i_{\phi m} \rightarrow \phi_m$$

$$i_p' \gg i_{\phi m}$$

$$i_p \cong i_p'$$



Em regime:

$$N_p \cdot i_p' = N_s \cdot i_s$$

$$N_p \cdot i_p = N_s \cdot i_s$$

$$\frac{i_p}{i_s} = \frac{N_s}{N_p}$$

Em termos de valores eficazes:

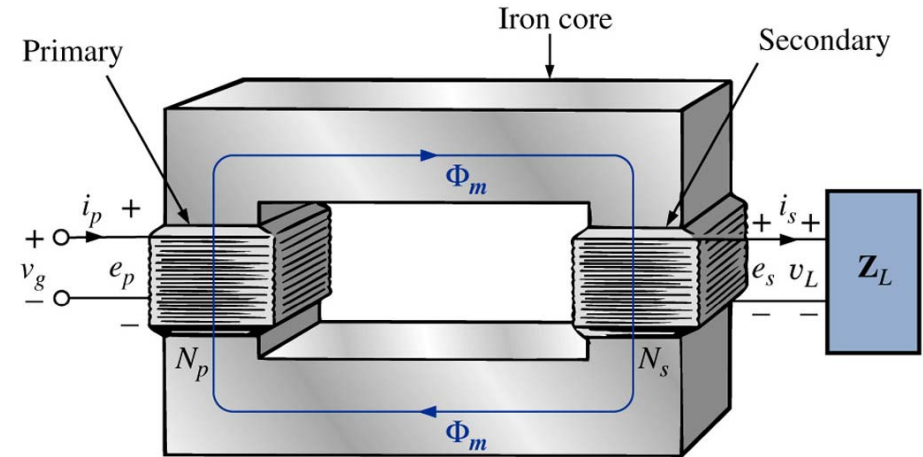
$$\frac{I_s}{I_p} = \frac{N_p}{N_s}$$

Transformador com núcleo de ferro

Relação das tensões:

$$\frac{e_p}{e_s} = \frac{N_p}{N_s}$$

A razão entre as tensões do primário e do secundário é diretamente proporcional à relação entre o número de espiras.



Relação das correntes:

$$\frac{i_p}{i_s} = \frac{N_s}{N_p}$$

A razão entre as correntes no primário e no secundário de um transformador é inversamente proporcional à relação de espiras.

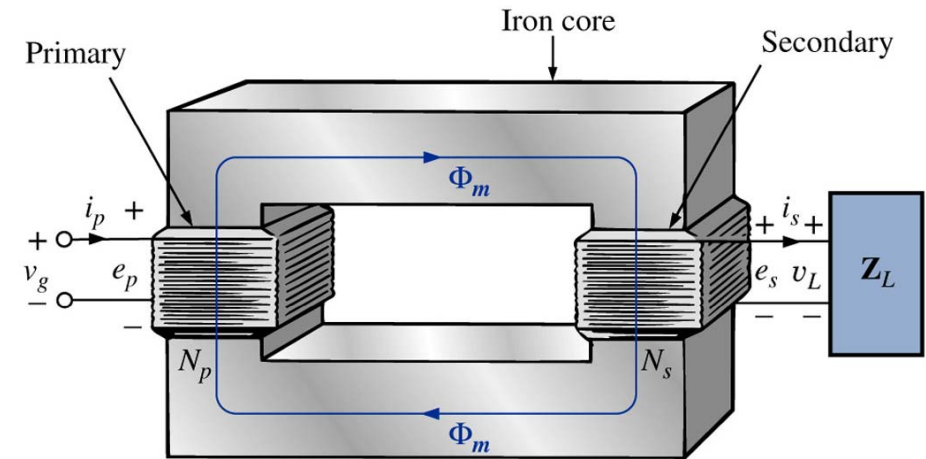
Transformador com núcleo de ferro

Impedância refletida:

$$\frac{\vec{V}_p}{\vec{V}_s} = \frac{N_p}{N_s} = a$$

$$\frac{\vec{I}_p}{\vec{I}_s} = \frac{N_s}{N_p} = \frac{1}{a}$$

$$\frac{\frac{\vec{V}_p}{\vec{I}_p}}{\frac{\vec{V}_s}{\vec{I}_s}} = \frac{a}{\frac{1}{a}} \longrightarrow \frac{\vec{V}_p / \vec{I}_p}{\vec{V}_s / \vec{I}_s} = a^2$$



$$\vec{Z}_p = \frac{\vec{V}_p}{\vec{I}_p} \quad \vec{Z}_s = \frac{\vec{V}_s}{\vec{I}_s}$$

$$\vec{Z}_p = a^2 \vec{Z}_s$$

Transformador com núcleo de ferro

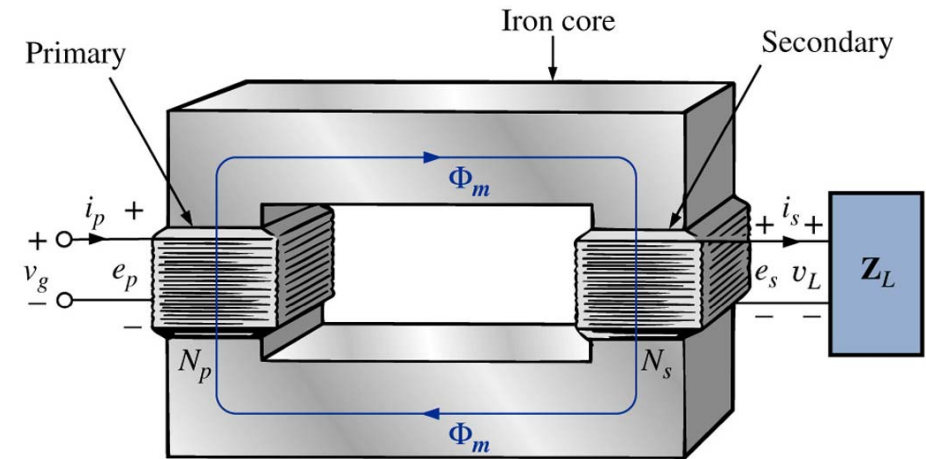
Potência (transformador ideal):

$$\frac{E_p}{E_s} = \frac{N_p}{N_s} = a = \frac{I_s}{I_p}$$

$$E_p \cdot I_p = E_s \cdot I_s$$


$$P_p = P_s$$

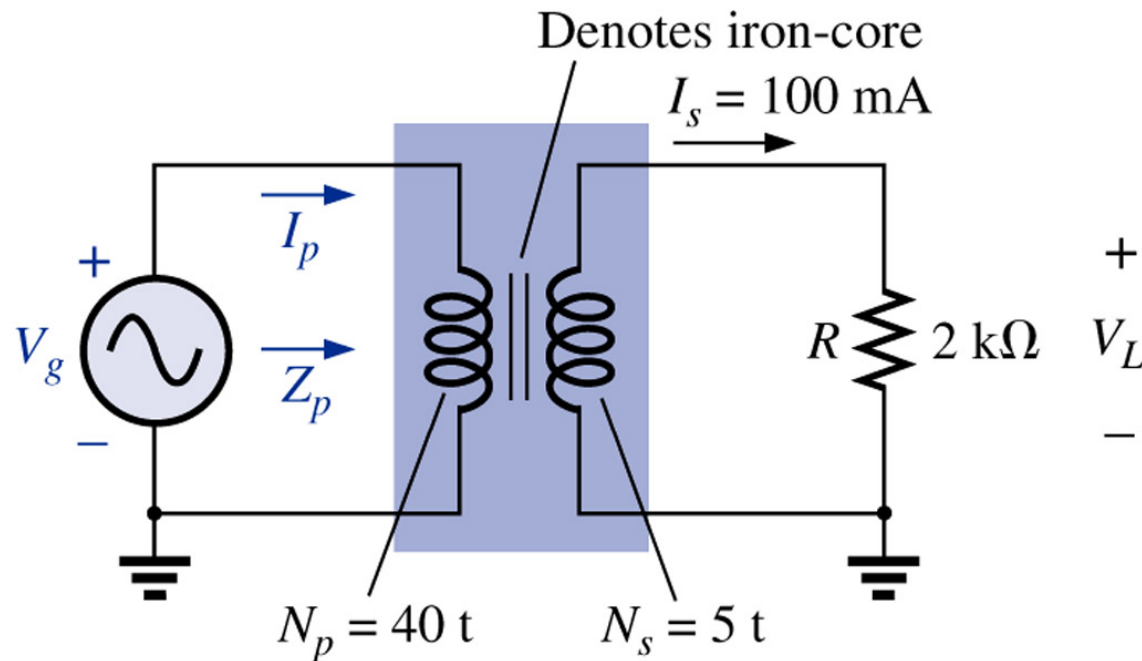
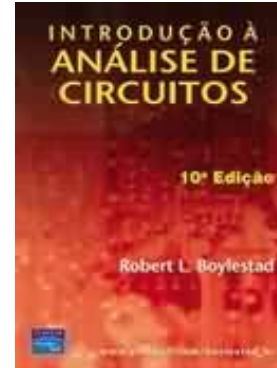
$$P_{\text{entrada}} = P_{\text{saída}}$$



Para um transformador ideal, a potência de entrada é igual a potência da saída, ou seja, o transformador não possui perdas.

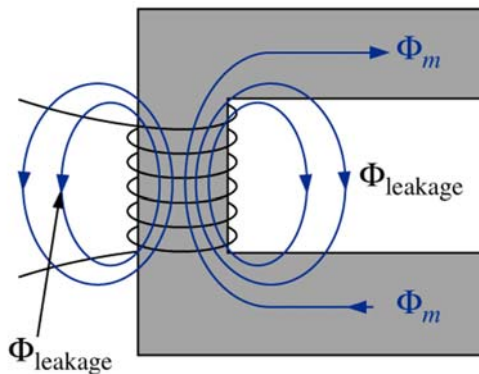
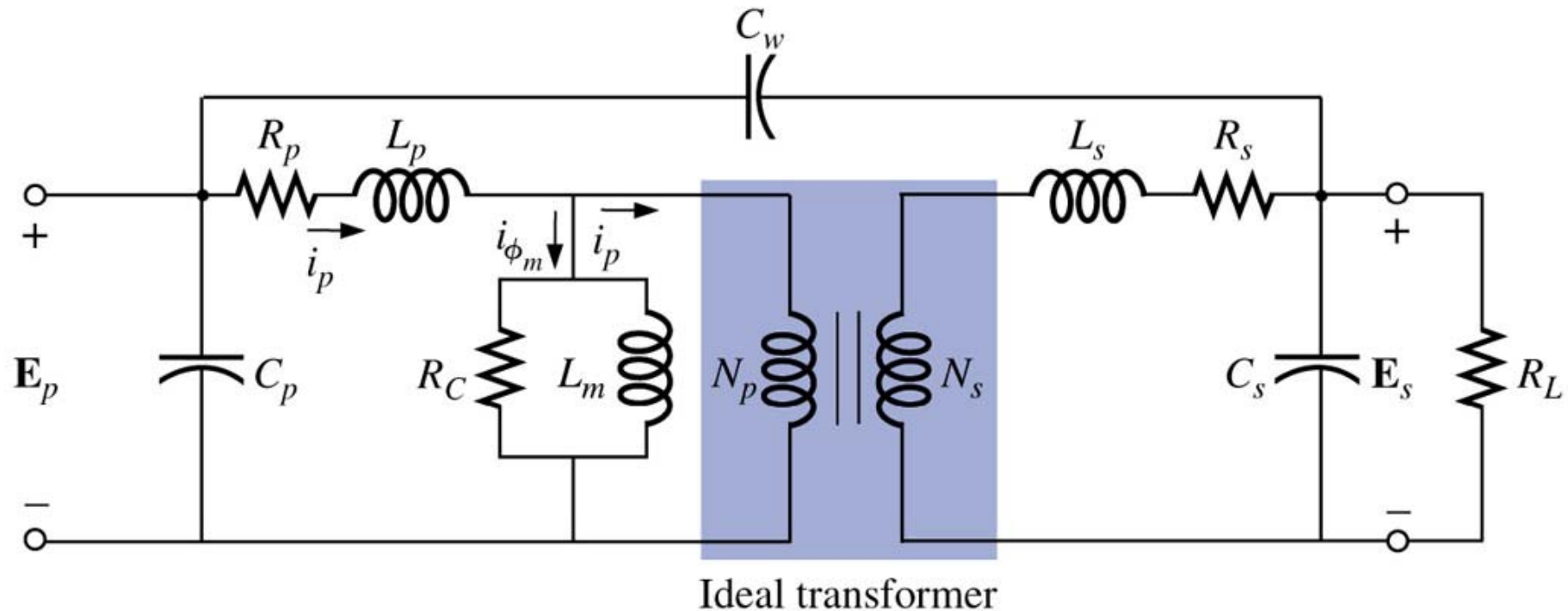
Transformador com núcleo de ferro

Exemplo 21.3, pag. 640: 



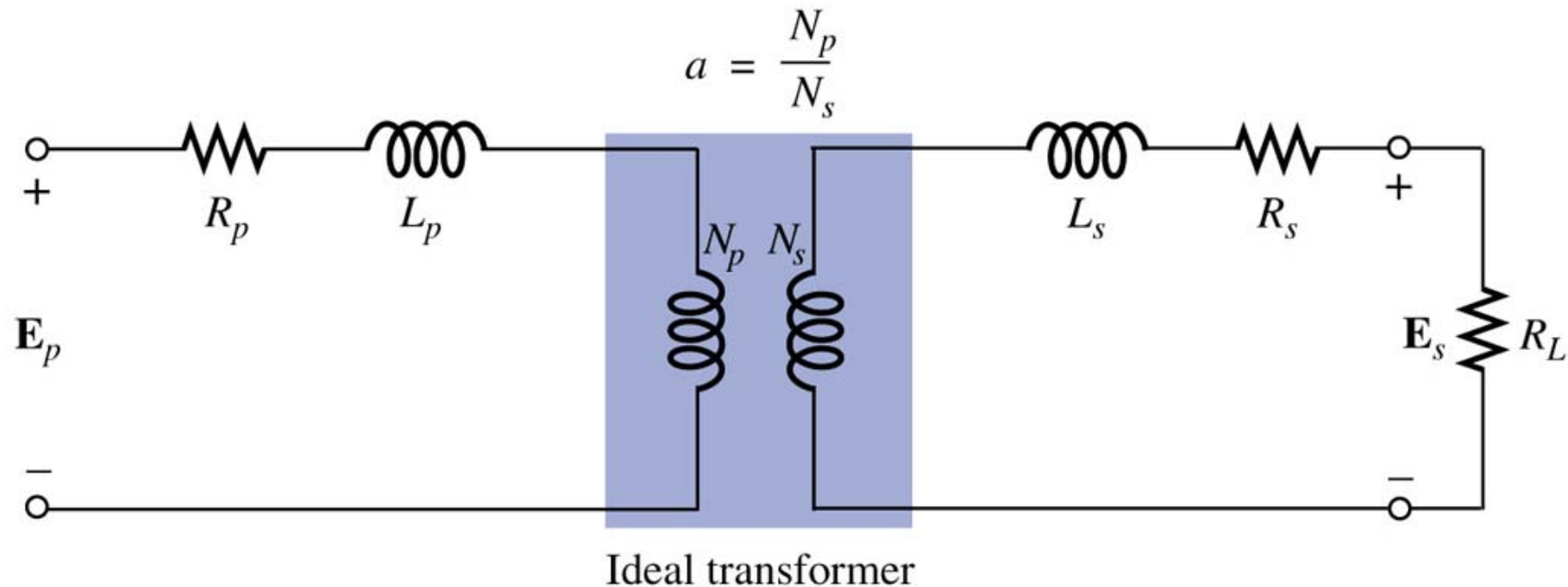
Circuito equivalente do transformador

Circuito equivalente completo de um transformador de núcleo de ferro real:



Circuito equivalente do transformador

Circuito equivalente reduzido do transformador de núcleo de ferro real:



$$R_{equivalente} = R_e = R_p + a^2 R_s$$

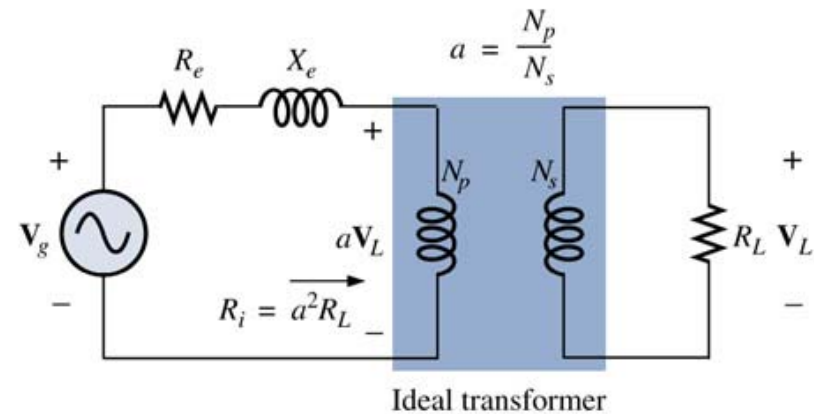
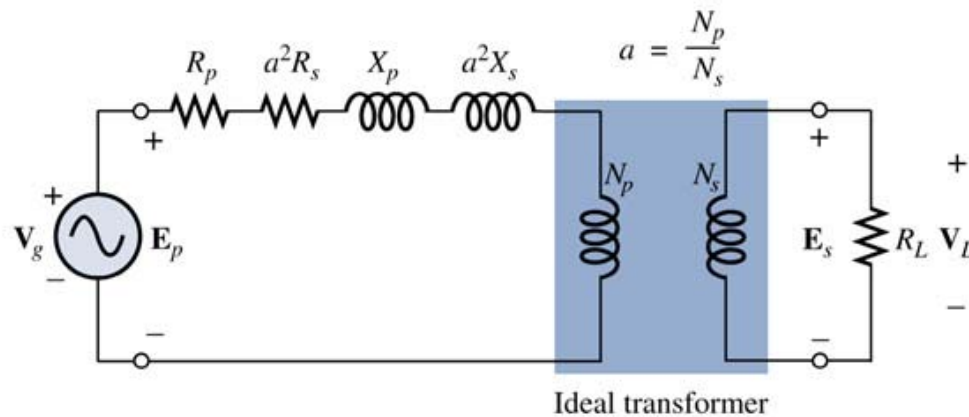
$$X_{equivalente} = X_e = X_p + a^2 X_s$$

Circuito equivalente do transformador

Circuito equivalente referido ao primário:

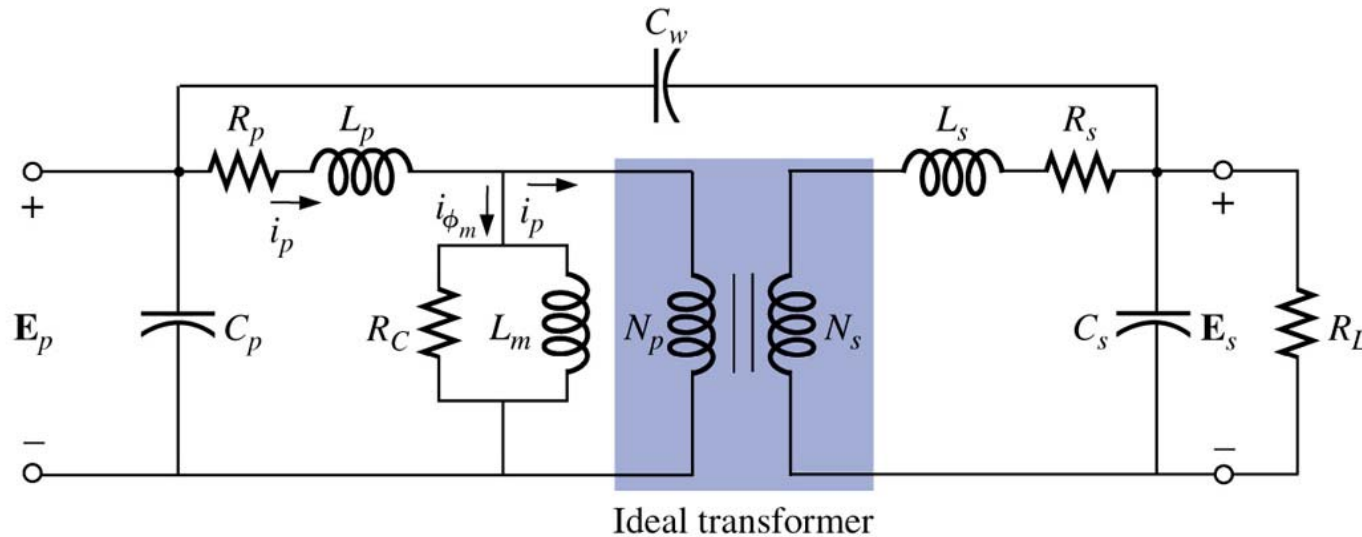
$$R_{equivalente} = R_e = R_p + a^2 R_s$$

$$X_{equivalente} = X_e = X_p + a^2 X_s$$

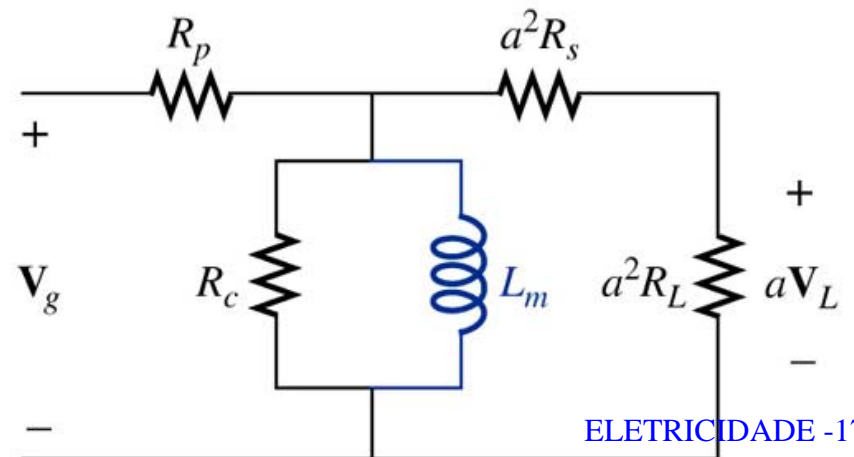


Circuito equivalente do transformador

Efeito da freqüência:

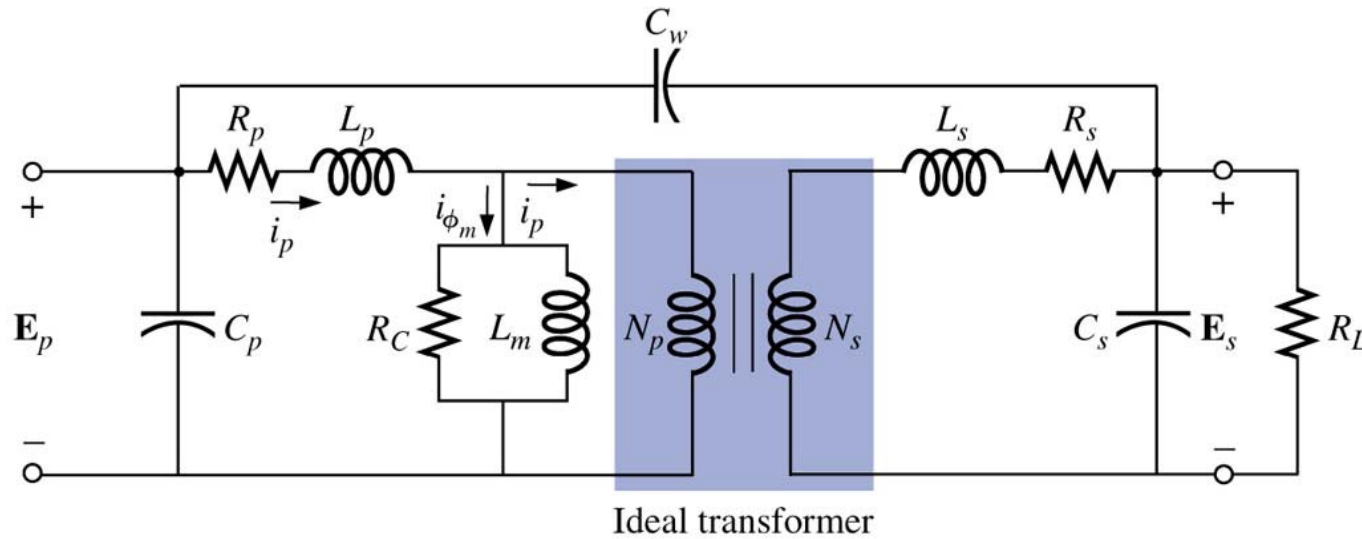


Circuito equivalente para baixas freqüências

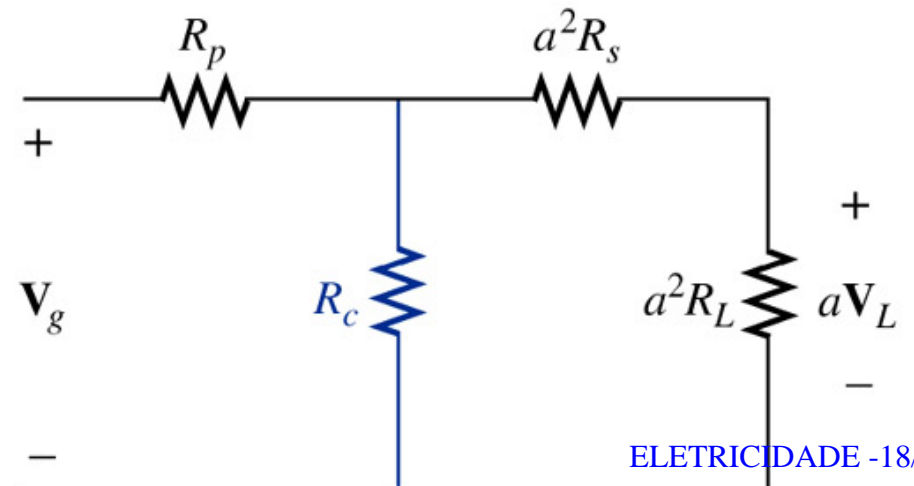


Circuito equivalente do transformador

Efeito da freqüência:

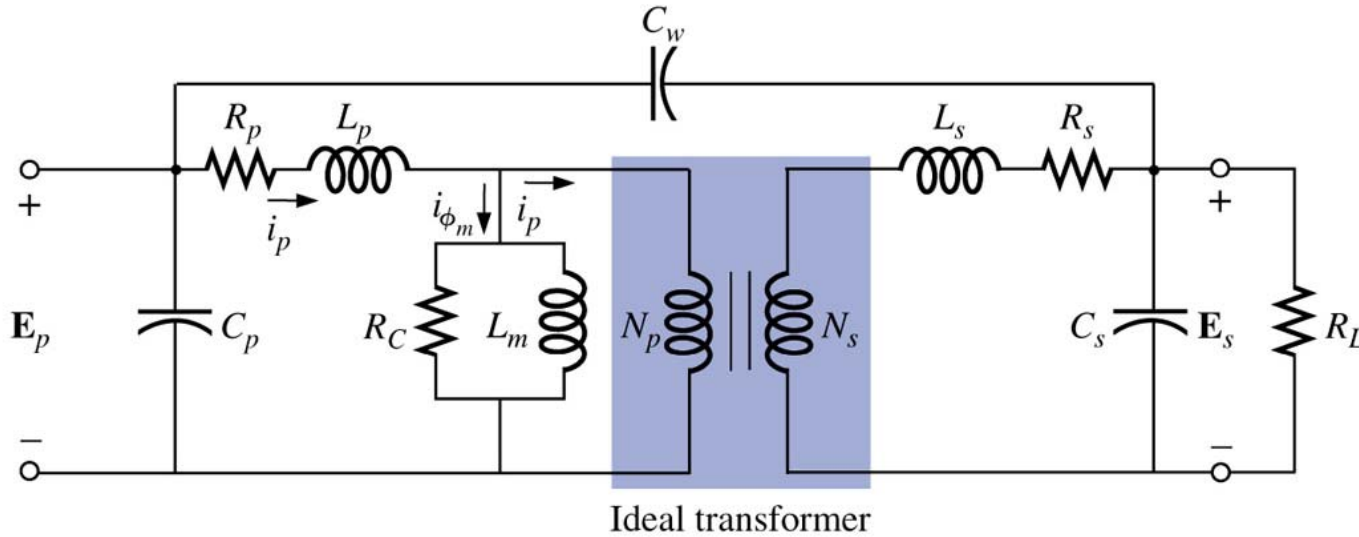


Circuito equivalente para médias freqüências

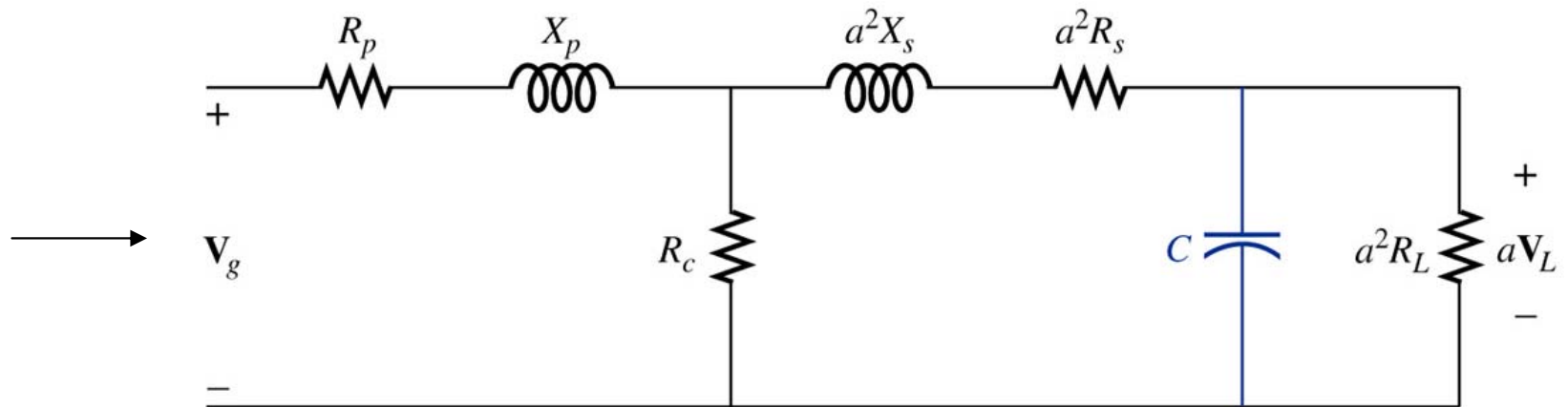


Circuito equivalente do transformador

Efeito da freqüência:

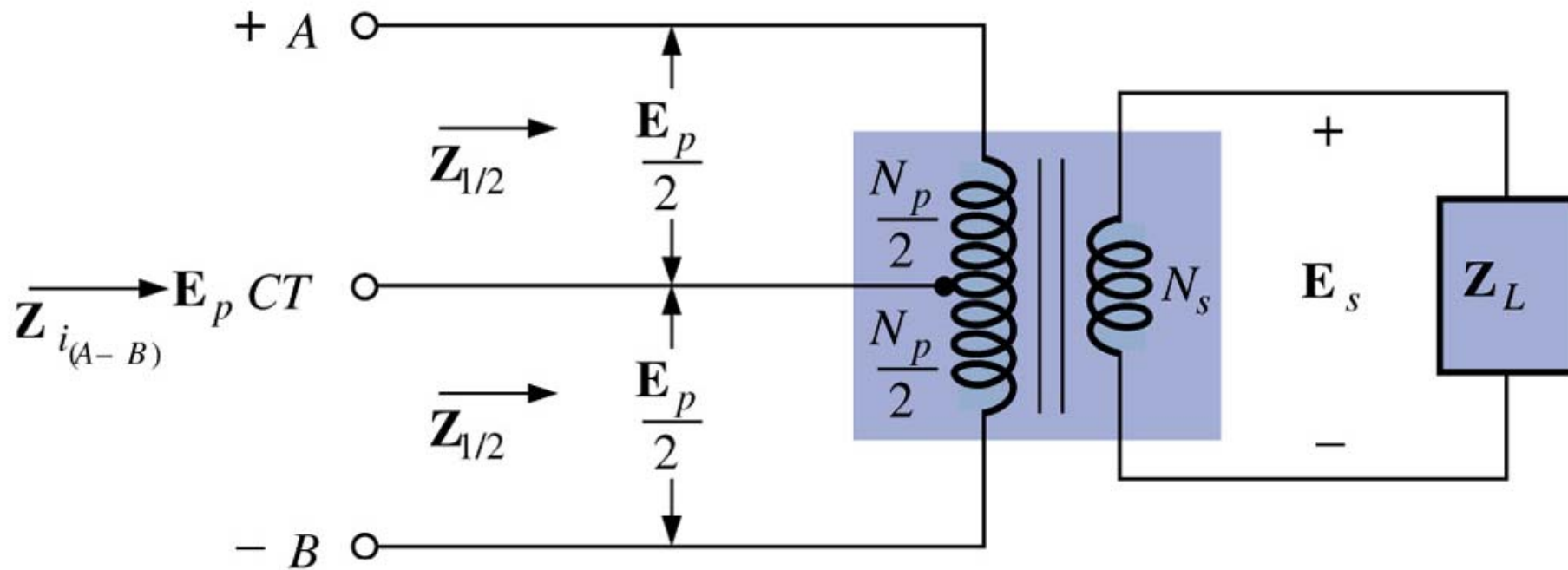


Circuito
equivalente
para altas
freqüências



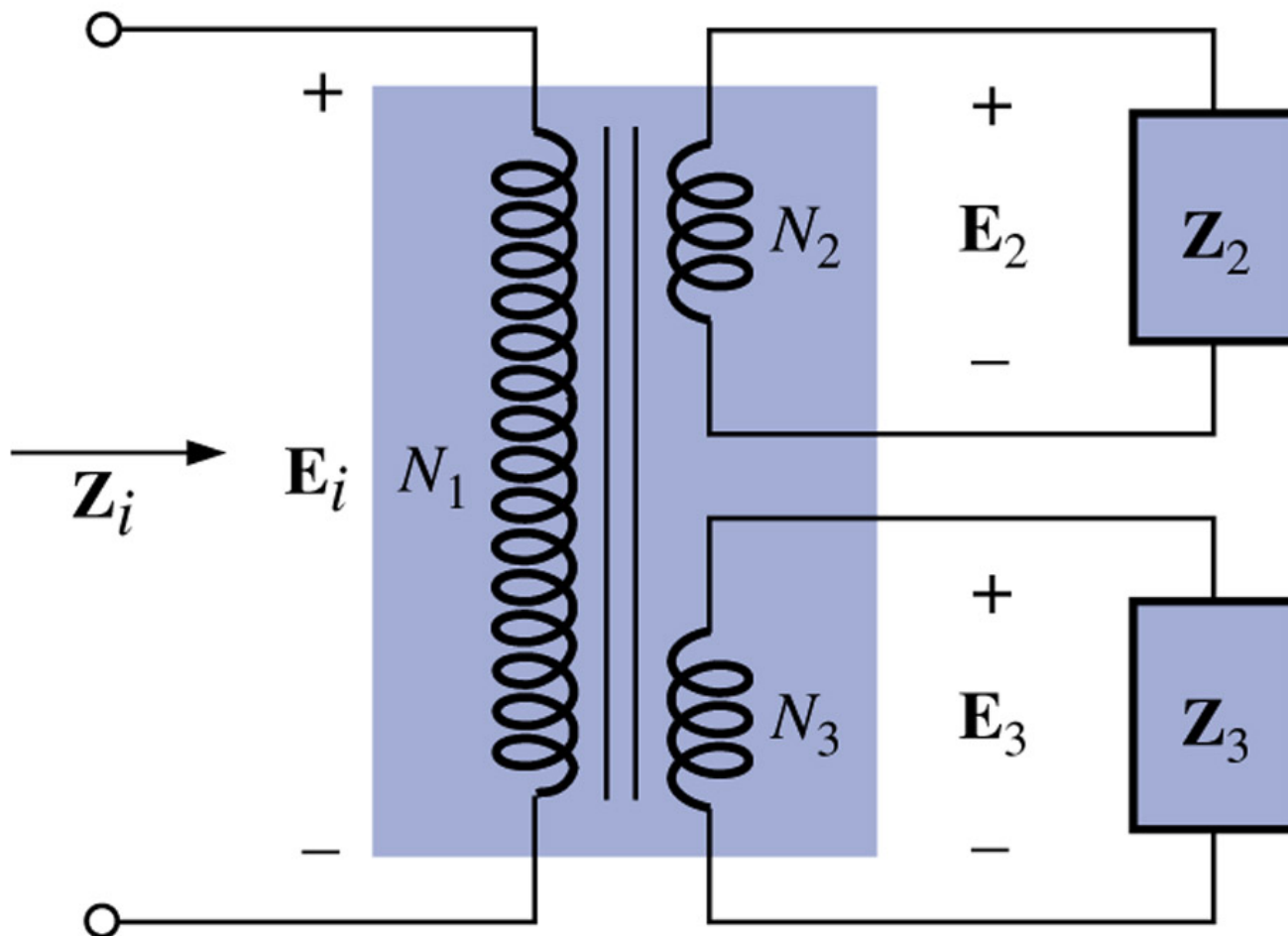
Tipos de transformadores

Transformador com derivação central:



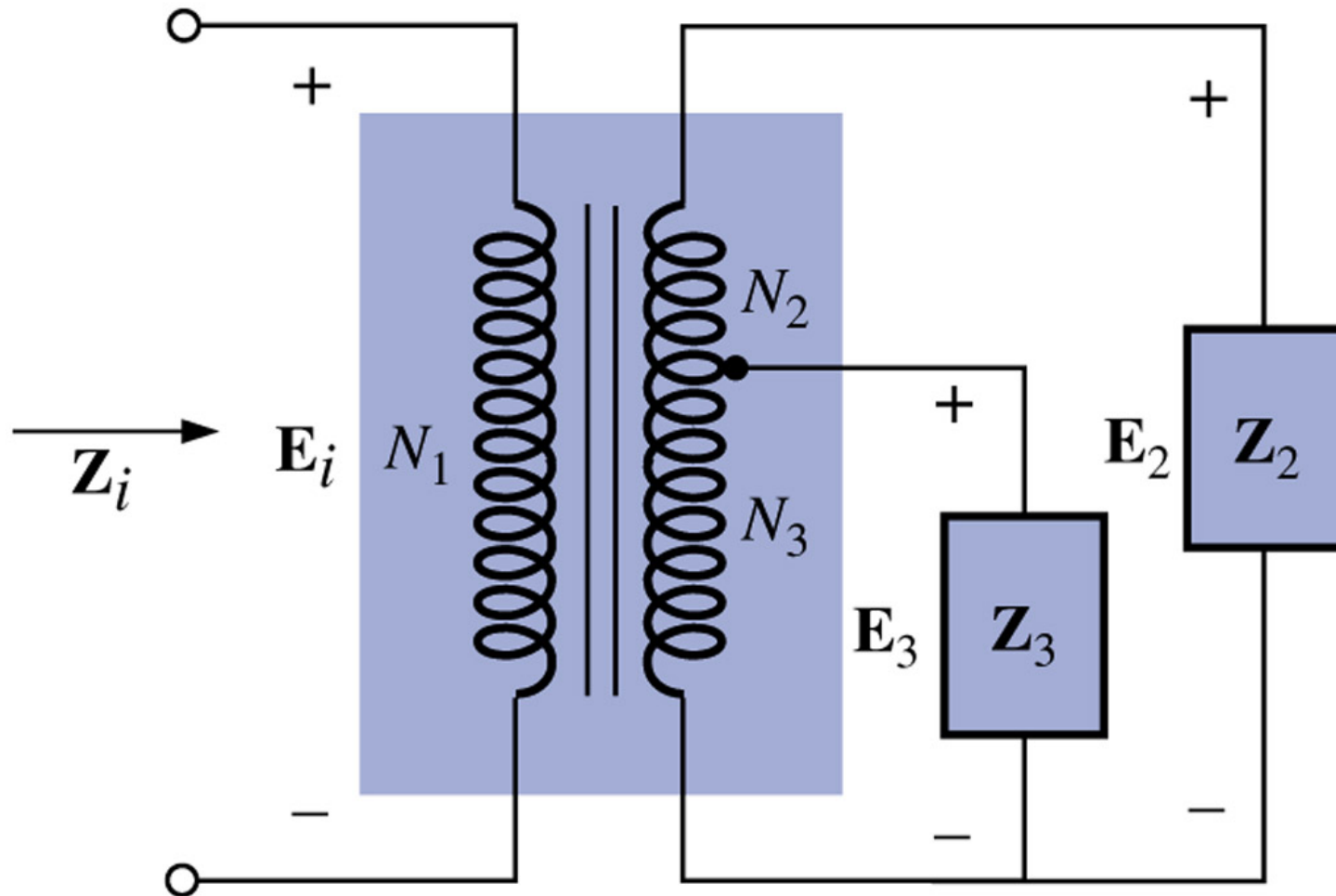
Tipos de transformadores

Transformador com dois secundários:



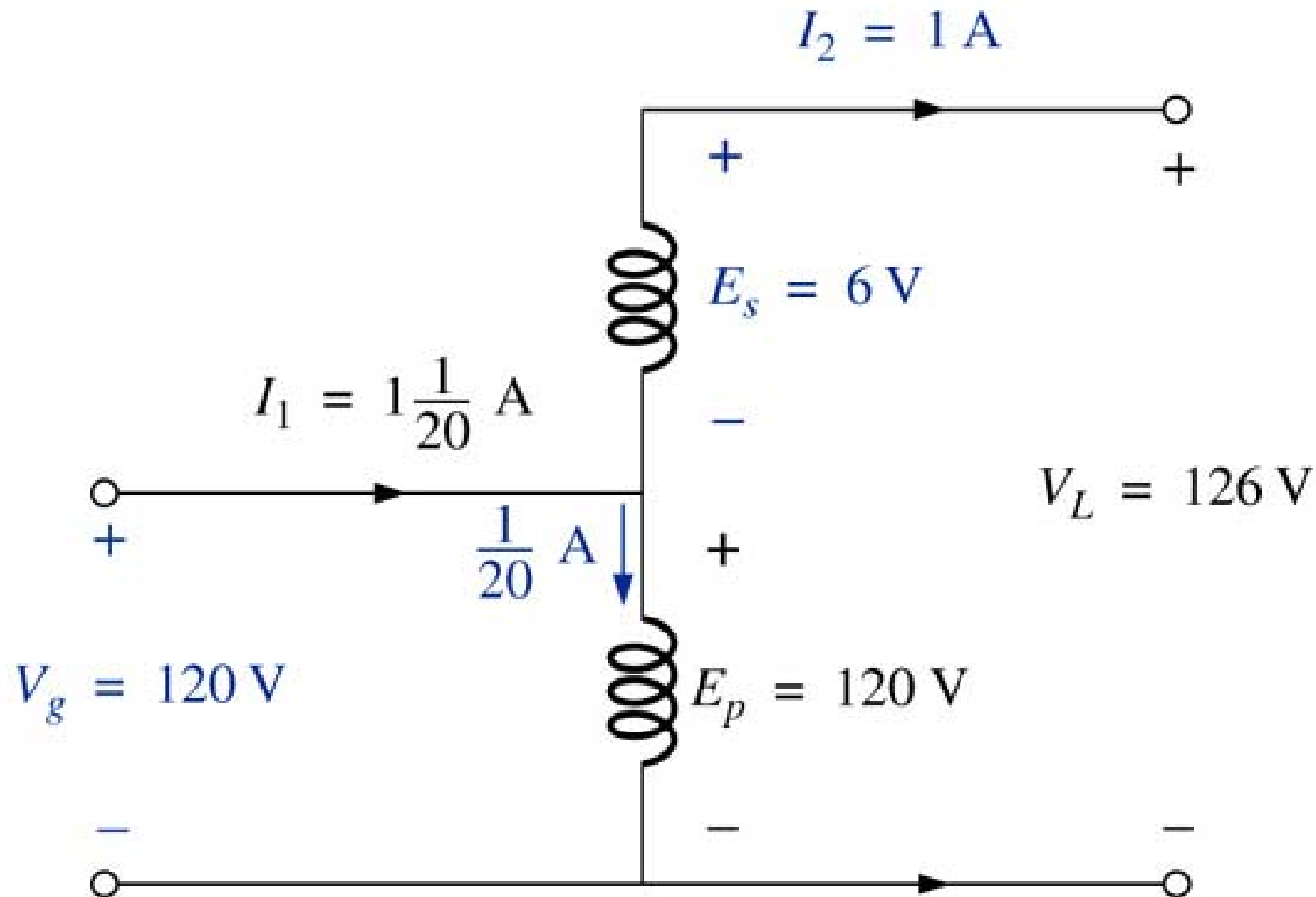
Tipos de transformadores

Transformador com derivação no secundário:



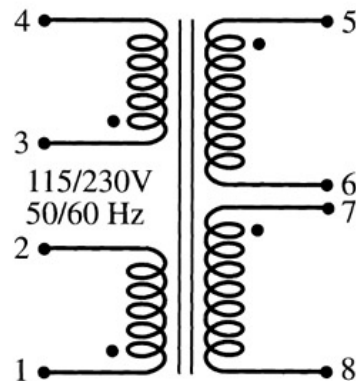
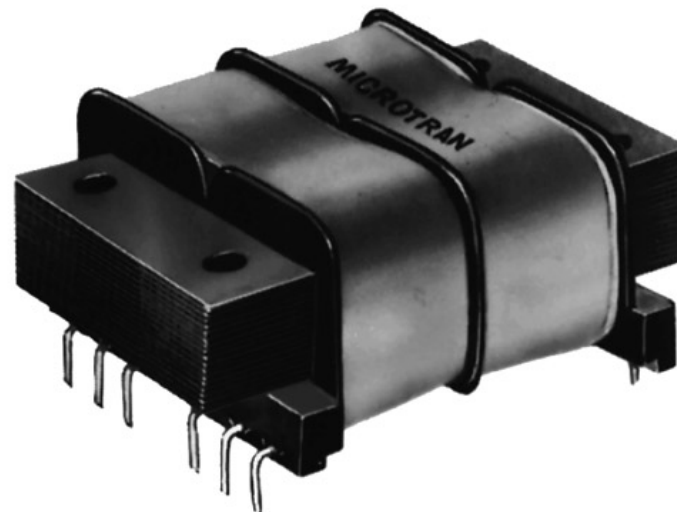
Tipos de transformadores

Autotransformador:



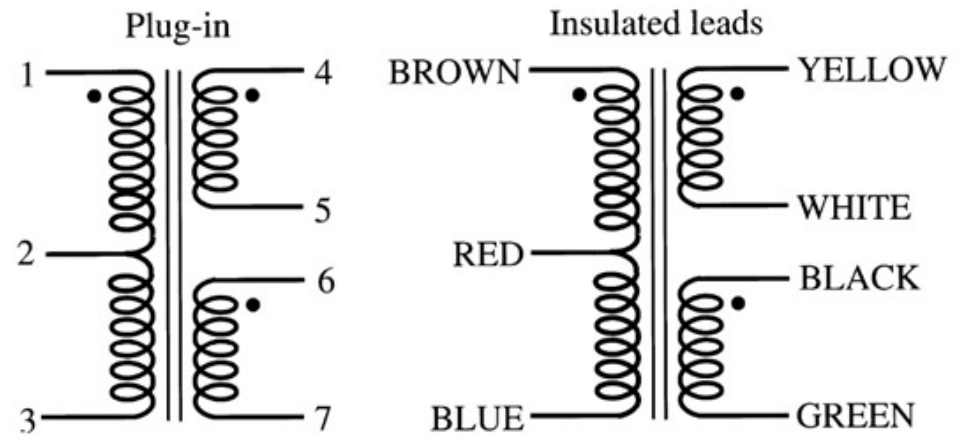
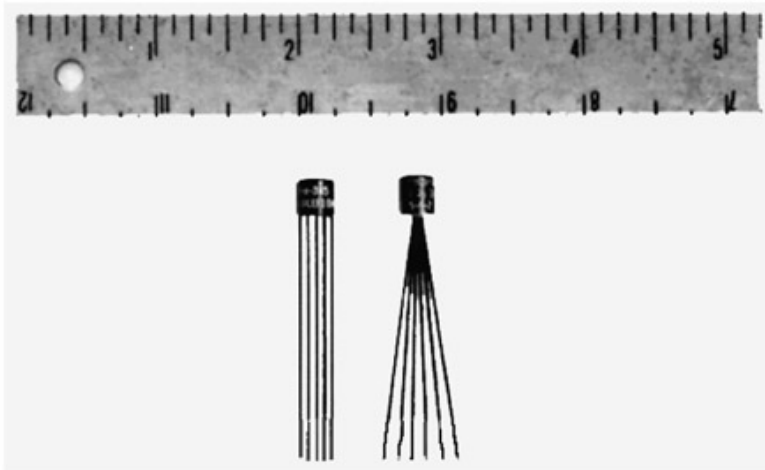
Tipos de transformadores

Transformador de pequenas dimensões com 2p e 2s:



Tipos de transformadores

Transformadores miniatura:



Tipos de transformadores

Transformador de pulsos:

