EE2022 Electrical Energy Systems

Principle of Transformers

Lecturer : Dr. Sangit Sasidhar (elesang)
Slides prepared by Dr. Panida Jirutitijaroen
Department of Electrical and Computer Engineering

Detailed Syllabus

Topic 1	**Transformer**: Principle of transformer. Ideal transformer. Reflected load. Impedance matching. Practical transformer. Examples
Topic 2	**Renewable Energy Sources:** Sustainable and clean energy sources; Solar Photovoltaic, Wind Energy; Examples
Topic 3	**Per unit analysis**: Single-phase per unit analysis. Three-phase transformer, Three-phase per unit analysis. Examples.
Topic 4	**Generator**: Simple generator concept. Equivalent circuit of synchronous generators. Operating consideration of synchronous generators, i.e. excitation voltage control, real power control, and loading capability. Principle of asynchronous generators. Examples.
Topic 5	Electric energy market operation; Cost of Electricity
Topic 6	**Distributed Generation:** Concept of distributed energy generation and utility interfacing; Energy Storage

Learning Outcomes

- Use electrical engineering principles to explain the **basic operation of** the electrical generator, transmission line and **transformers** in an electrical energy system and **able to identify and construct their equivalent circuits** appropriately.

Outline

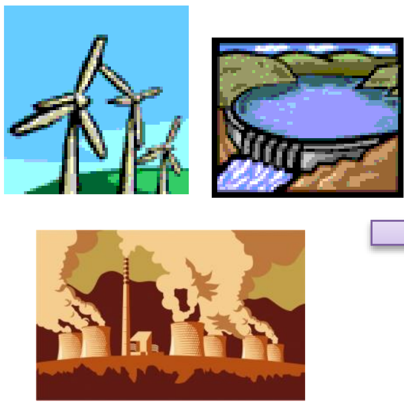
- Principle of Transformers
- Ideal Transformers
  - Equivalent circuit
  - Turns ratio

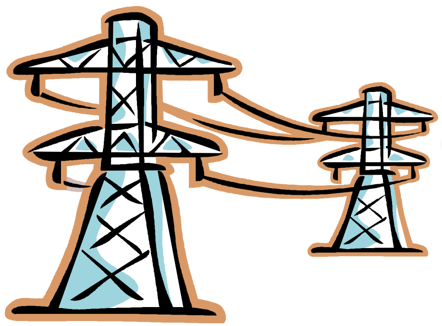
Electrical Energy Systems

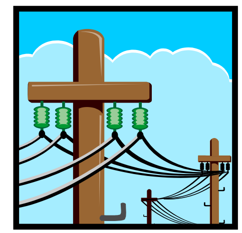
Generation (11 – 36 KV)

Transmission (110 – 765 KV)

Distribution (120/230 V – 138 KV)







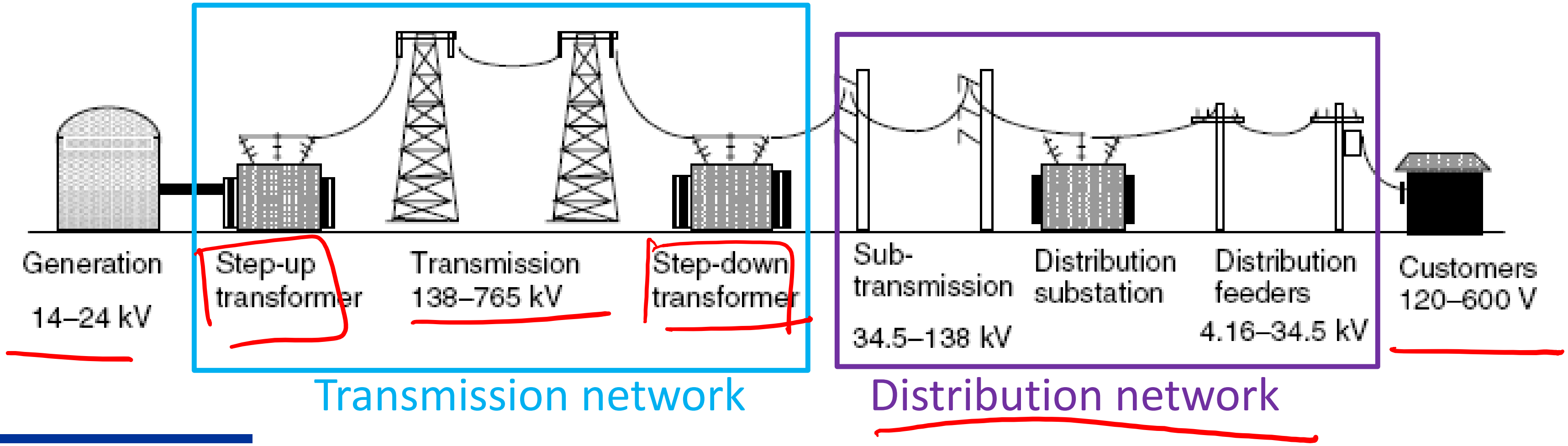
Large-Scale Power Plants:
Coal-fired, Hydro, Wind,
Solar, Nuclear

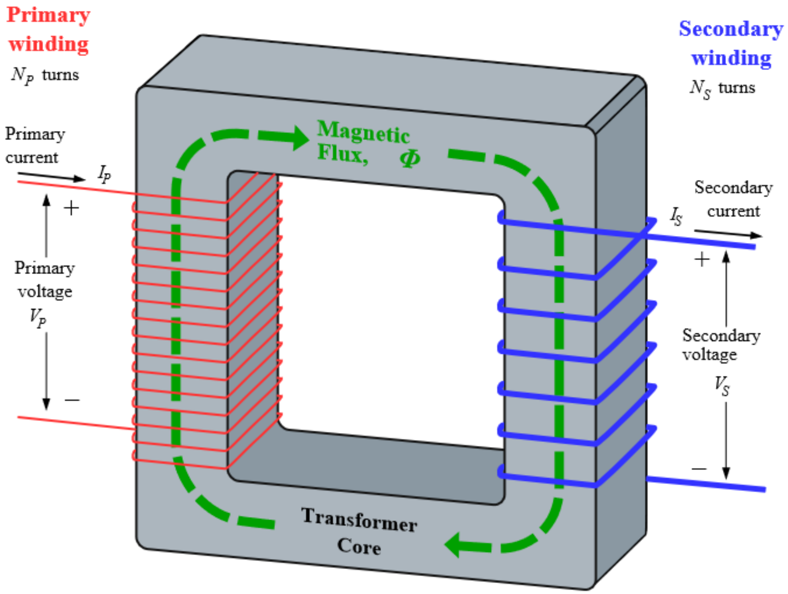
Industrial customer (23 – 138 KV)
Commercial customer (4.16 – 34.5 KV)
Residential customer (120 – 240 V)

How to connect generation (medium voltage) to transmission (high voltage) to the point of consumption (low voltage)?

Why Transformers???

- Transformers are used to step up voltages from generation units to transmission-line and to step down voltage from transmission to end users.
- Transformers are important in electrical energy systems. With transformers, the overall efficiency can be improved.
  - Lab Experiment 2!!



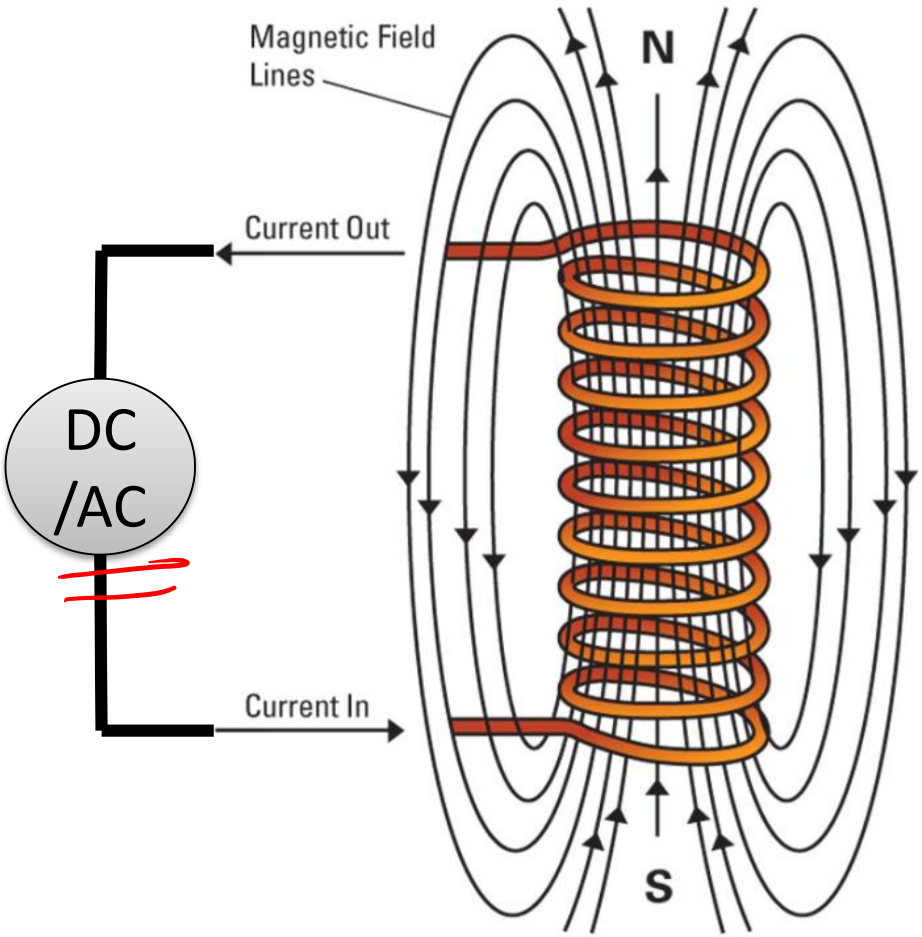


Electromagnetism
Electromagnetic induction
Dot notation
Faraday's Law
Ampere's Law

PRINCIPLE OF TRANSFORMERS

Source: "Transformer3d col3" by BillC at en.wikipedia - Own workTransferred from en.wikipedia. Licensed under CC BY-SA 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Transformer3d_col3.svg#mediaviewer/File:Transformer3d_col3.svg

Electromagnetism



- DC source → Constant magnetic flux
- AC source → Varying magnetic flux

What will happen if we have another coil to link the varying magnetic flux?

Source: http://www.lanl.gov/news/index.php/fuseaction/1663.article/d/20085/id/13276

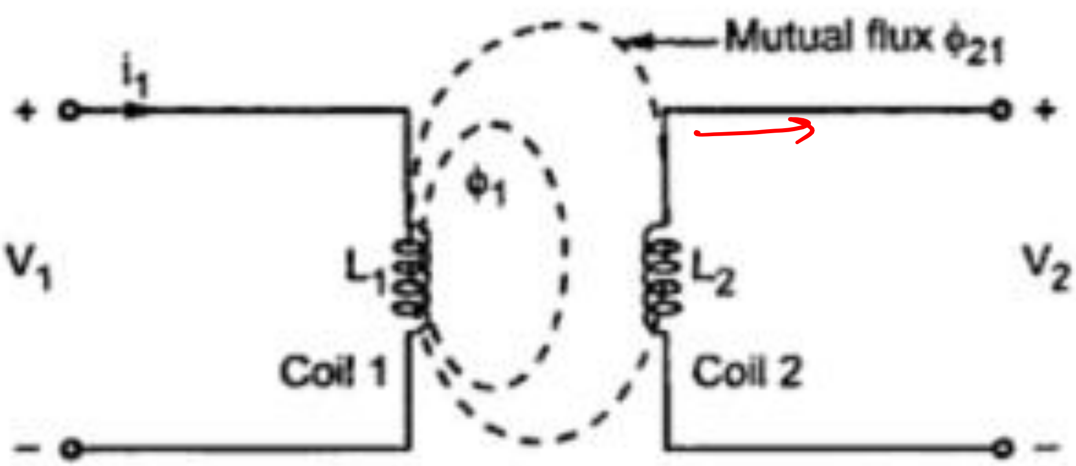
Electromagnetic Induction

- Recall Faraday's law:

$$e = N\boxed{\frac{d\phi}{dt}}$$

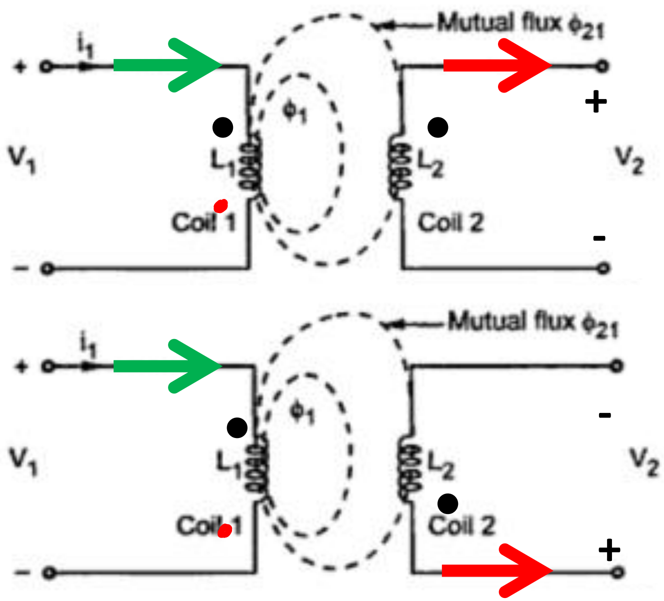
- When we link Coil 2 to the magnetic flux generated by coil 1, if the flux is varying, there will be induced electromotive force (EMF) V_2, at Coil 2.

Source http://yourelectrichome.blogspot.com/2011/07/introduction-to-coupled-circuit.html



Dot Notation in Transformers

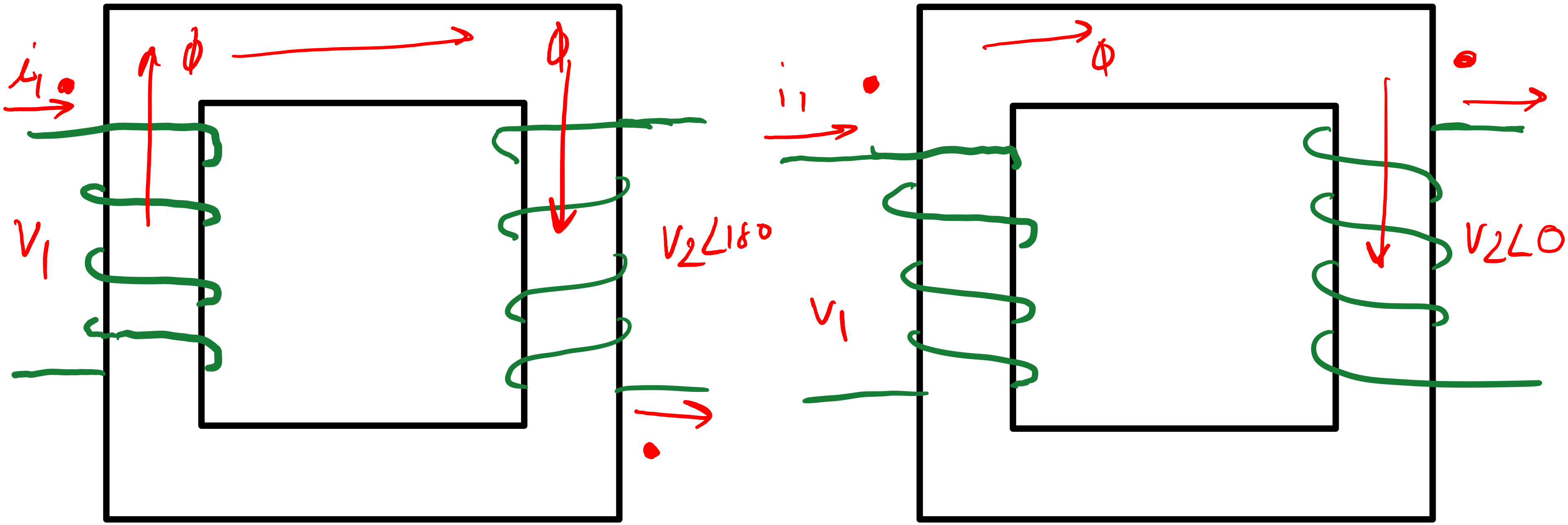
- **Dot notation** is used to indicate the direction of current out of Coil 2 in the equivalent circuit.



$V_1\angle 0$ $V_2\angle 0$

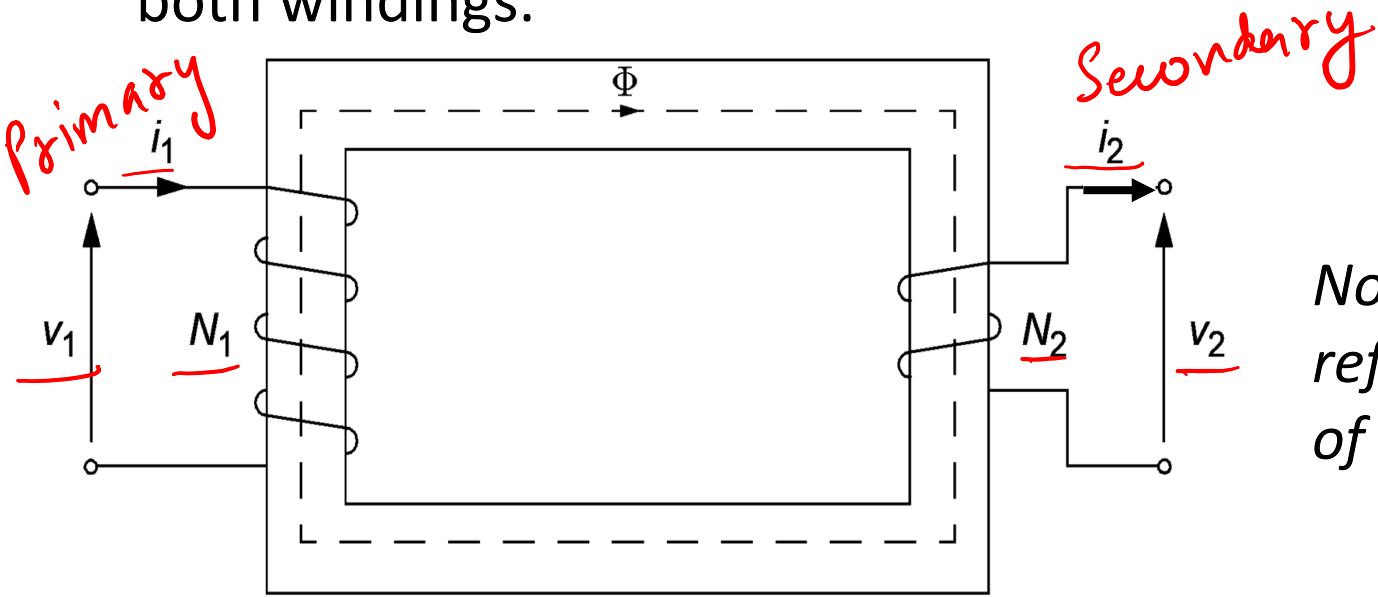
$V_1\angle 0$ $V_2\angle 180$

Dot Notation in Transformers



Magnetic Core

- We can better link the magnetic flux by using magnetic core.
- Magnetic flux "Φ" is now confined in the core and links both windings.



Note that 'N' refers to number of turns.

We are now interested to relate V1 and V2, and relate i1 and i2.

Faraday's Law

- Recall that: $$e = N\frac{d\phi}{dt}$$

$$\phi = \sqrt{2}\,\phi \cos\omega t$$

$$e = -N\sqrt{2}\,\phi\omega \sin\omega t = N\sqrt{2}\,\phi\omega \cos(\omega t + 90)$$

$$E = N\phi\omega \angle \underline{90^\circ} = N\phi(\underline{j}\omega)$$

$\phi = B\,A \rightarrow$ Area m^2 $\Rightarrow$ $\boxed{E = N\,B\,A\,j\omega}$

B ↓ Magnetic Flux density wb/m^2

Voltage Relationship

- For **ideal** transformer, we assume that the flux linkage at coil 1 and coil 2 is the same i.e. there is no flux linkage loss.
- We can now find a relationship between the voltages at two sides of the transformer as follows.

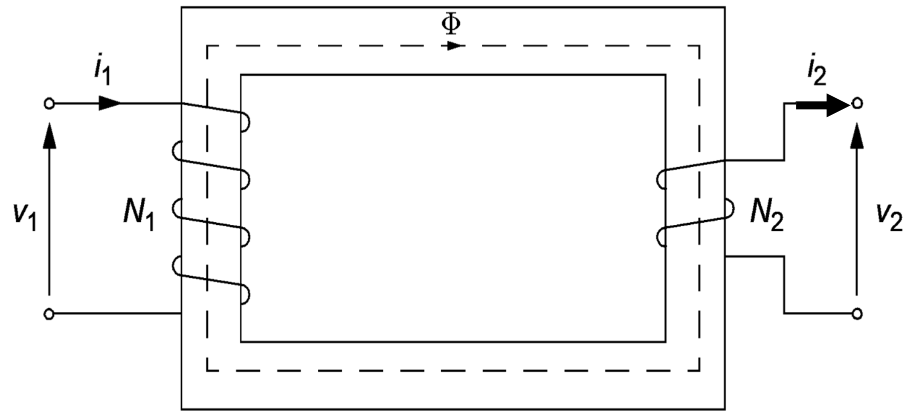
Primary

$V_1 = N_1 \underline{\phi_1} j\omega = N_1 B A j\omega$

Secondary

$V_2 = N_2 \underline{\phi_2} j\omega = N_2 B A j\omega$

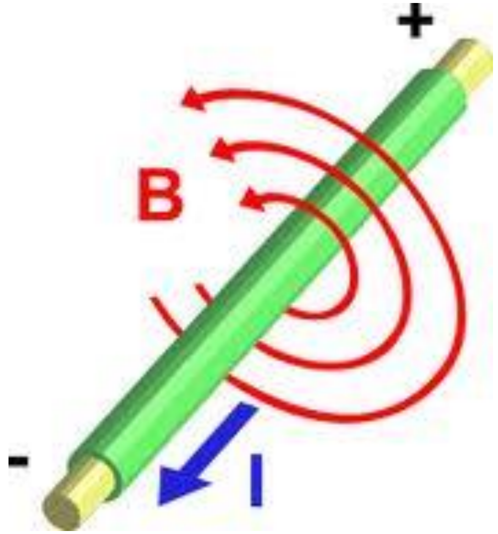
$$\boxed{\frac{V_1}{V_2} = \frac{N_1}{N_2}}$$



Ampere's Law

- "Current passing through a conductor creates magnetic field around it "

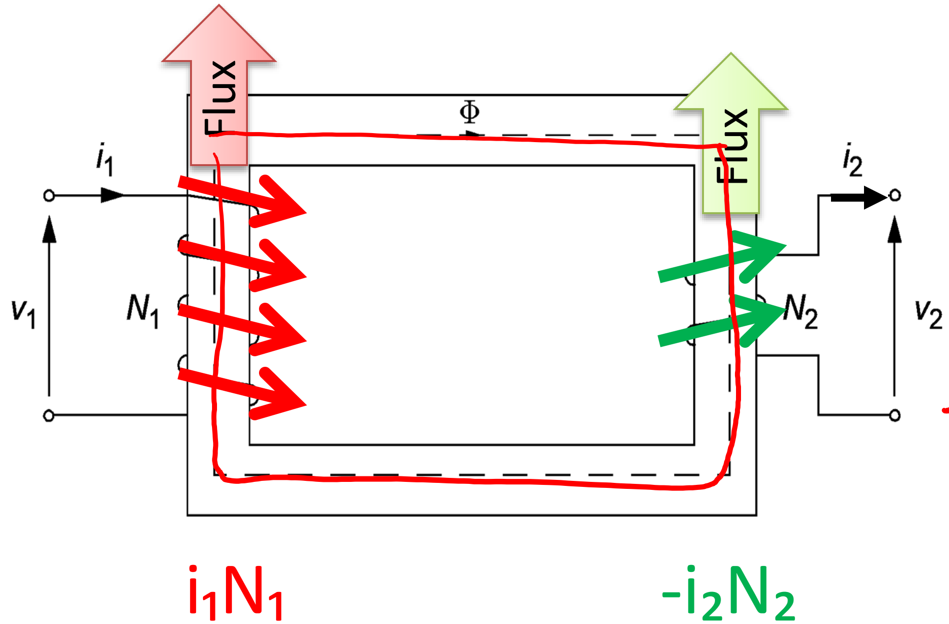
$$\oint H dl = I_{enclosed}$$



- B = μH
- B = Magnetic flux density (Weber/m^2 or Tesla)
- H = Magnetic field intensity (A/m)
- μ = Magnetic core permeability (H/m)

Ampere's Law Applied to Transformers

- "Magnetic flux along the path equals the net current enclosed by the path"



$$H\, l_{path} = I_{enclosed}$$

$$H\, l_{path} = I_1 N_1 - I_2 N_2$$

$$\frac{B}{\mu} l_{path} = I_1 N_1 - I_2 N_2$$

Current Relationship

- Note that magnetic core permeability (μ) represents the degree of magnetization that the magnetic core will allow the magnetomotive force to pass through.
- For **ideal transformer**, the value of the permeability is infinity. $\mu \to \infty$

$$\boxed{\frac{B}{\mu} l_{path}} = I_1 N_1 - I_2 N_2$$

$$\downarrow$$

$$0$$

$$I_1 N_1 = I_2 N_2$$

$$\frac{N_1}{N_2} = \frac{I_2}{I_1}$$

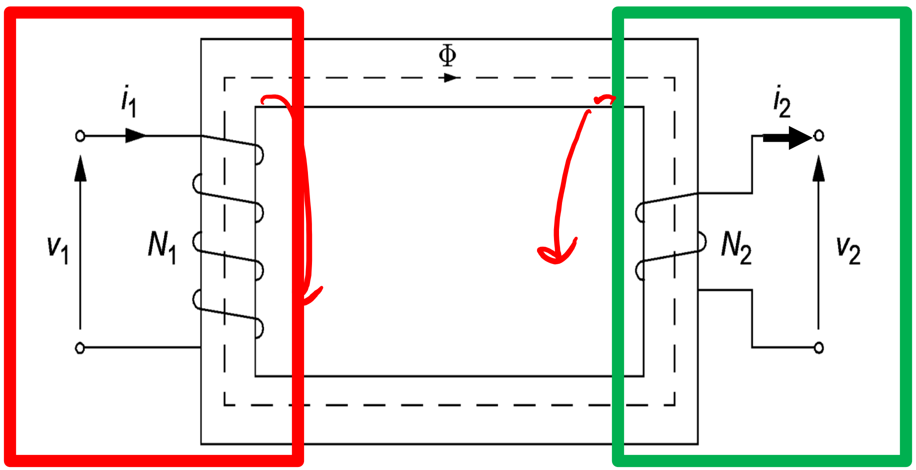
Assumption

Turns ratio

IDEAL TRANSFORMERS

Assumptions

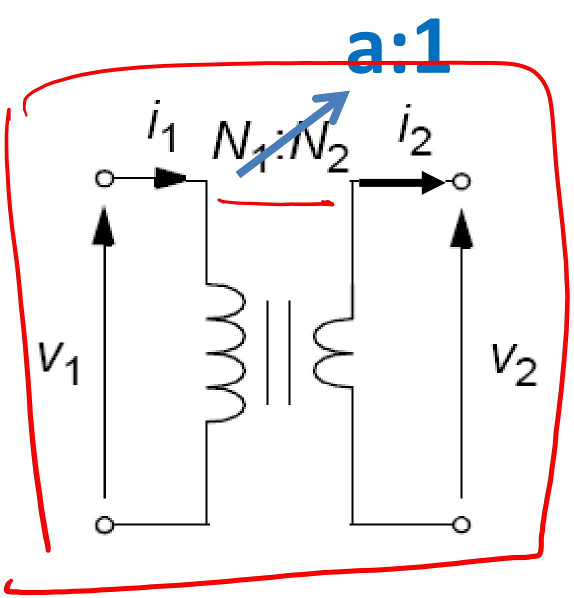
1. No resistance in both windings.
2. No leakage flux around the core.
3. No core resistive loss.
4. Core permeability is infinite.



$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \qquad i_1 N_1 = i_2 N_2$$

Turns Ratio

- We represent an equivalent circuit of an ideal transformer as shown below.



- Define turns ratio as:

$$a \equiv \frac{N_1}{N_2}$$

$\frac{\text{Primary}}{\text{Secondary}}$

- From Faraday's and Ampere's Law:

$$\boxed{\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2} = a}$$

Complex Power

- Complex power *at* *primary side*,

$$\underline{S_p} = V_1 I_1^*$$

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = a$$

$$V_2 = \frac{V_1}{a}$$

- Complex Power at *secondary* side

$$\frac{I_2}{I_1} = \frac{N_1}{N_2} = a$$

$$\Rightarrow I_2 = a \cdot I_1$$

$$\underline{S_S} = V_2 I_2^* = \frac{V_1}{a} (a I_1)^*$$

$$= V_1 I_1^*$$

No real or reactive loss

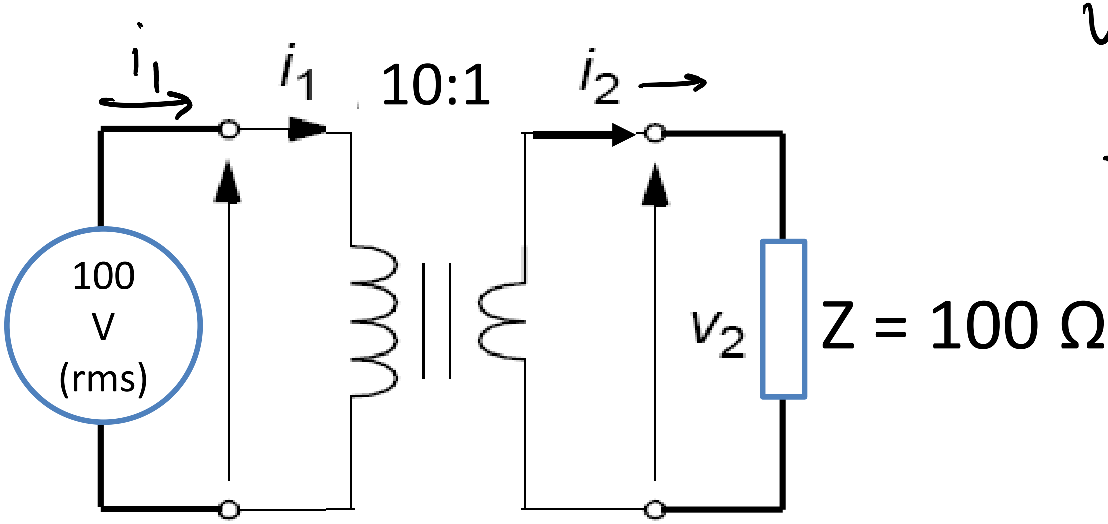
Example 1

- From the circuit below, what is the current at the secondary and primary side?

$V_1 = 100V \qquad a = 10$

$V_2 = \frac{V_1}{a} = 10V$

$i_2 = \frac{10}{100} = 0.1A$



$i_1 = 0.1/10$

$= 0.01A$

100×0.01

1 W

10×0.1

1 W

Summary

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$\frac{I_2}{I_1} = \frac{N_1}{N_2}$$

$$\frac{N_1}{N_2} = a$$

Complex power for an ideal transformer

$$S_{primary} = S_{secondary}$$