*Teaching a Course on*

# Transformers in Power Systems

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# Existing Power Systems
# Course Structure in Texas Tech:


- 15,000 sq. ft laboratory space
- HV Sources, Fast oscilloscopes and digitizers,
  Advanced electromagnetic field solvers, High speed cameras

- Current research topics:

1. Explosive studies
2. Active rail-gun control
3. Security sensitive weapon development
4. Optimization of semiconductor switching, etc.

- Course structure:

i. 3 main undergrad course – PP, PE, PS

ii. 2 main grad courses – PP, PE
- PS (Special topic)

iii. **This Fall:**
EE 5332 – Power Systems Dynamics and Stability

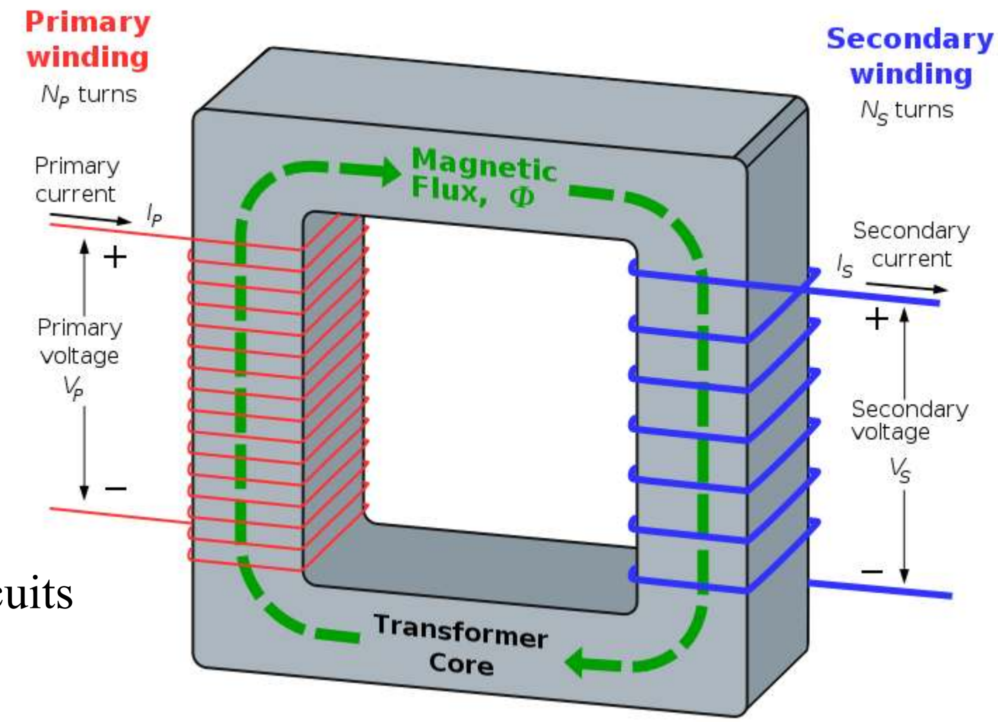
**Spring 2010:**
EE 5340 – Power System Identification

# Transformers and Impedance Matching

**Definition:**

- An Electro-magnetic circuit that provides the right voltage for the operation of an electric system

- Can be used to
  - match impedance between circuit & load, two circuits
  - provide isolation
  - match balanced & unbalanced circuits




**3 main headings:**

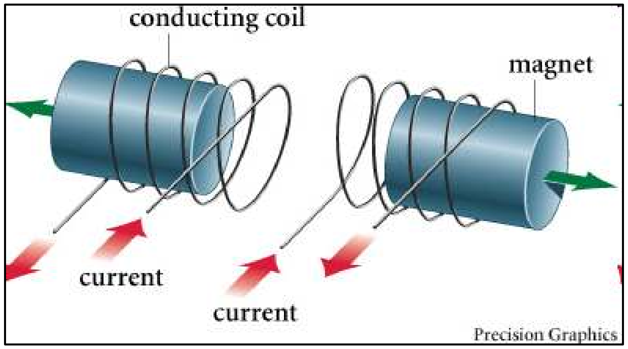
i. Principle of Operation
ii. Transformer core & geometry
iii. Types and Applications

All three involve numerical problem solving as well as essay-type (descriptive) questions

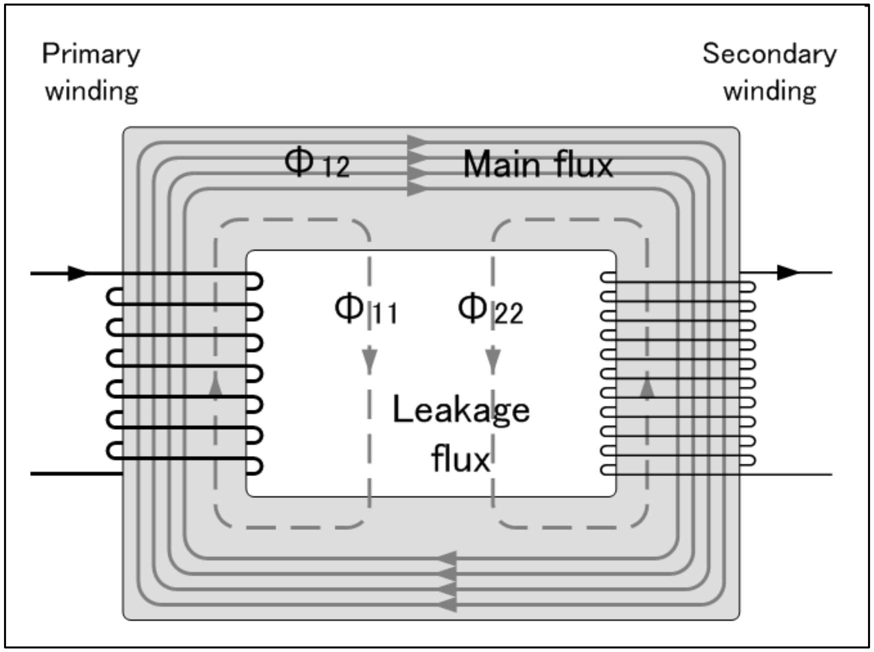
# i. Principle of Operation

# Principle of Operation

- Faraday's Law of Electromagnetic Induction




When two wires are brought close to each other and one of them carries a fluctuating current, a current will be induced in the other wire.




- The primary and secondary coils are wrapped around an iron core of very high magnetic permeability.

- Since the same magnetic flux passes through both the **P** and **S** in an ideal transformer,

$$V_p = N_p \frac{d\phi}{dt}, \quad V_s = N_s \frac{d\phi}{dt}$$

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$ **Turns ratio**

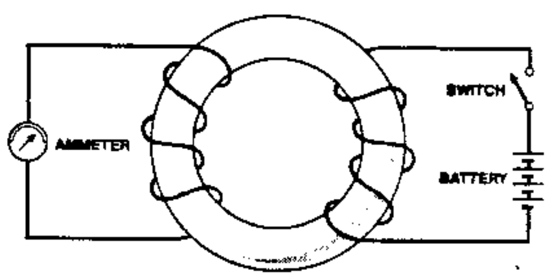
$$V_p I_p = I_s V_s$$ **Power balance**

# Principle of Operation

→ Students must get familiar with transformer phasor diagrams from the start

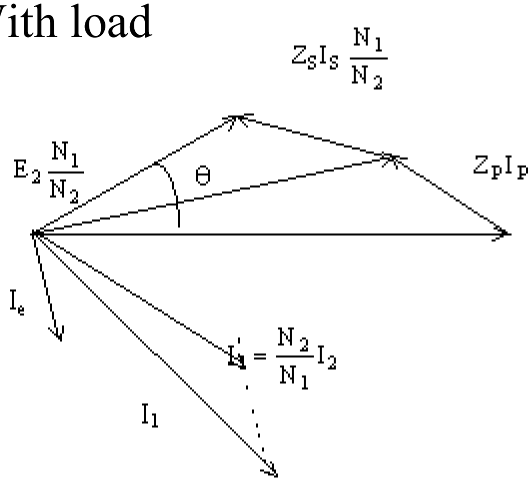
→ An excellent way to do this is to teach **No-load** and **On-load** operation in the first few warm-up classes

- No-load




- What is a no-load condition?
- What currents flow through the primary/secondary?
- Are they in phase or out of phase with voltage?
- What is the frequency of the exciting current?
- How does the phasor diagram look like?

- With load

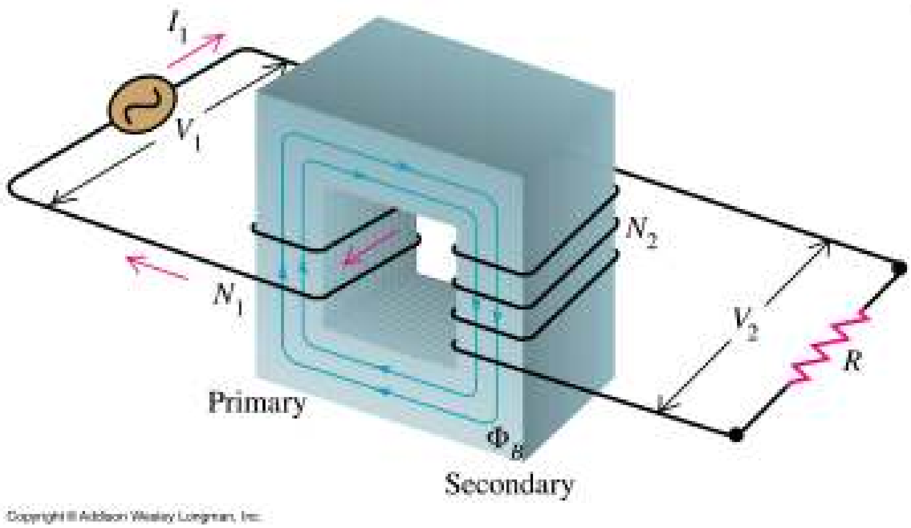



- Extra induction due to secondary current?
- What about current phases/frequency?
- Inductive and Capacitive loads?

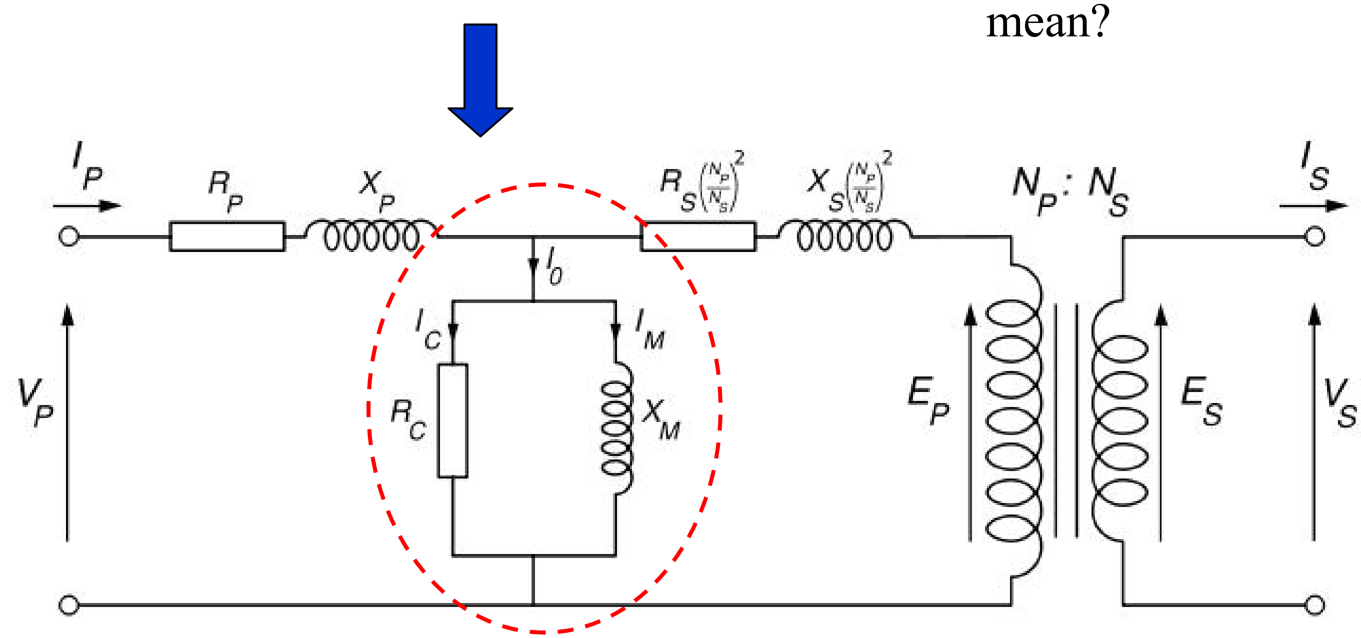
$I_e$ = magnetizing current
$I_e$ = magnetizing current

Next: Magnetic Leakage

# How to Interpret a Transformer Electrically?

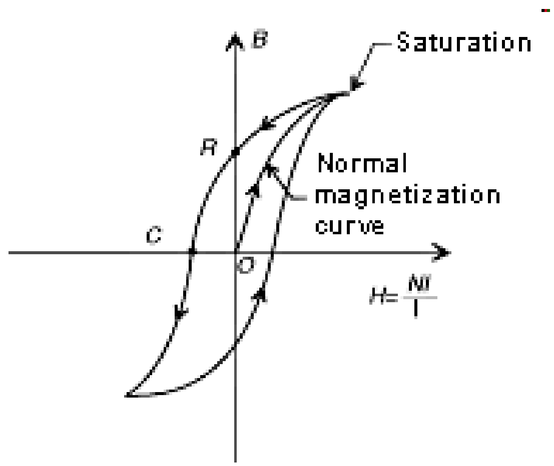



- Electrical Engineers look for resistance and reactances, & circuit structure
- Gives them confidence in viewing the physical system mathematically
- What do each resistance and reactance mean?




* Why parallel?
* When can be neglected?
* What effect on operation?

# What is the Problem with DC?




• Hypothetically an ideal transformer would work with direct-current excitation, but

Recall Faraday's Law

$$V_p = N_p \frac{d\phi}{dt} \Rightarrow \phi = \int_0^t \frac{V_p}{N_p} dt = \frac{V}{N_p} t$$

Monotonic increase in flux!

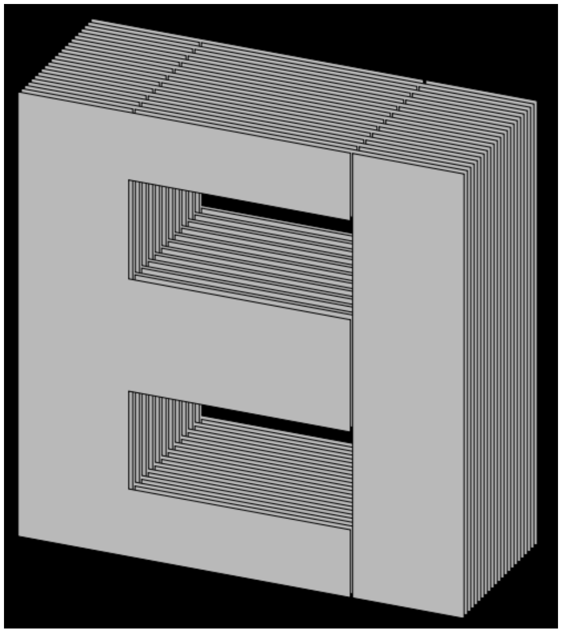
• In practice, the flux would rise to the point where **magnetic saturation** of the core occurs, causing a huge increase in the magnetizing current and overheating the transformer.

AC excitation produces bounded periodic flux, avoiding this problem

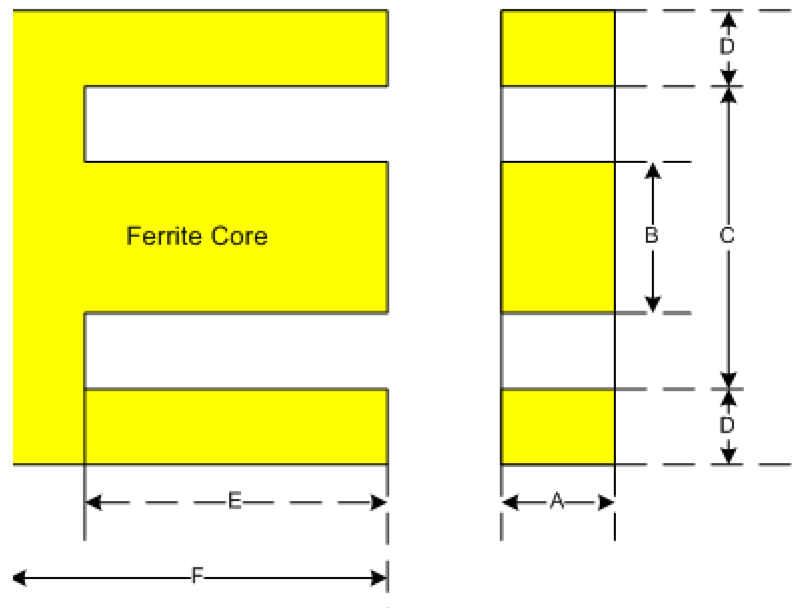
• DC Transformer or DC/DC Converter (boost, buck) are realized through power electronic devices

# ii. Transformer Core and Geometry

# Transformer Core & Geometry



• Ferromagnetic core increases the flux coupling far more than air core




• Utility transformers (60 Hz operation) typically use E-core
  – Shell winding (maximum coupling, high efficiency)
  - Core winding (higher voltage)

• Other types – Solenoid core, O-core, Pot core, Toroidal core (higher frequency)

# Numerical Problems on T/R Geometry

- Optimization of Geometry for enhanced performance
- Detailed dimensioning
- Understanding the importance of each step of design
- Detailing will take time

SPICE Software

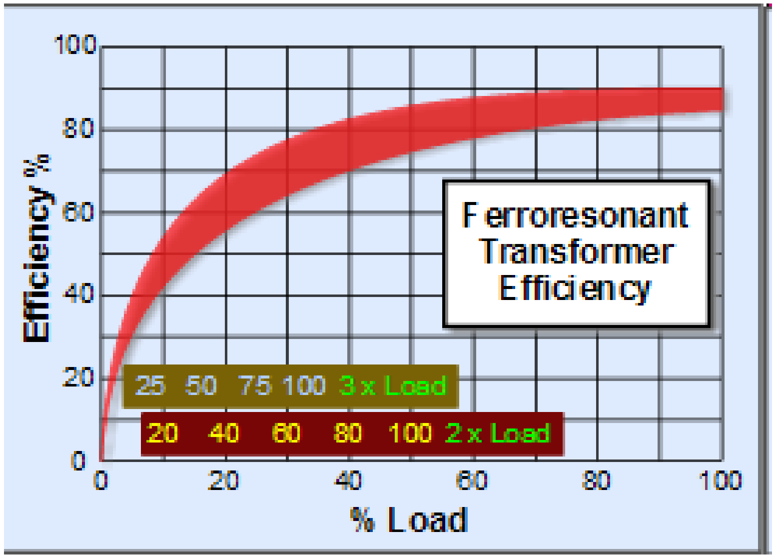
Can be taught as a *separate computer-oriented* **design** course (Ex: Senior capstone project)

**Main Steps:**

1. Determine core size
2. Evaluate peak flux density
3. Compute turn ratio
4. Compute coil size, losses
5. **Iterate!**

Magnetizing current below given value?

# Transformer Losses & Efficiency




**Losses:**

1. Core loss/Iron loss
   - includes hysteresis and Eddy current loss
   - practically same for all loads

2. Copper loss:
   - due to resistance in windings
   - proportional to current square

**Efficiency = 1 – loss/input** → loss is in VA, input is in Watts, so efficiency is dependent on power factor

$$= 1 - \frac{x/\cos\phi}{1 + x/\cos\varphi}$$ (φ = secondary pf, $x = V_2 I_2/\text{loss}$)

• Condition for Maximum Efficiency:

→ Copper loss = Iron loss ⇨ An effective way for students to evaluate their individual designs

# All-day Efficiency

Transformer design is an excellent chance to learn about All-day efficiency

$$\eta_{ad} = \frac{\text{output in } KWh}{\text{input in } KWh} \quad \text{(for 24 hours)}$$

- Distribution transformers supply no load at night
- Only core loss, very little copper loss
- All-day efficiency captures this effect based on the extent the t/r is **used** in a day

Numerical Example:

500 KVA t/r, Cu loss=4.5KW, Fe loss=35. KW at full load. Daily loading is:

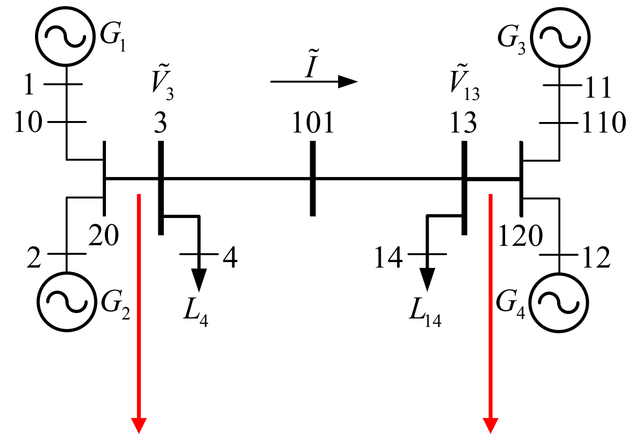
- 400 KW (0.8 pf) for 6 hours
- 300 KW (0.75 pf) for 10 hours
- 100 KW (0.8 pf) for 4 hours
- 4 hours of no load

Calculate ADE

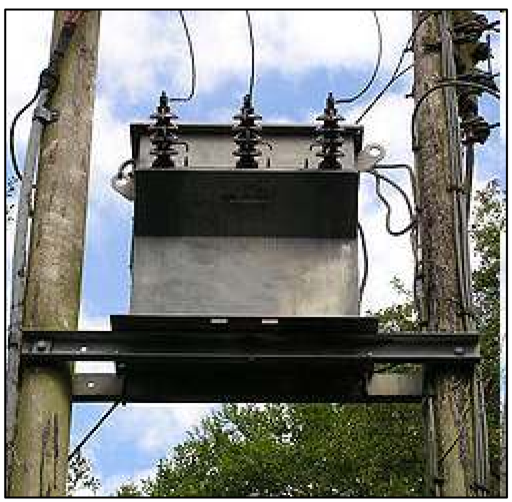
# iii. Transformer Types and Applications in Power Systems

# Transformer Types & Applications

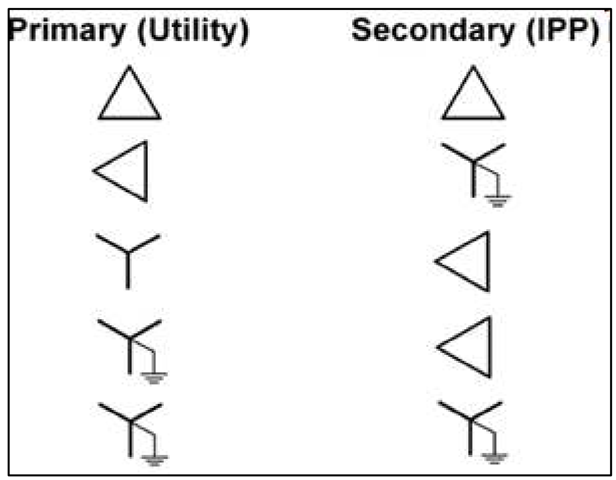
1. Power Transformers
2. Distribution Transformers
3. Isolation Transformers
4. Auto-transformers




## Power Transformer

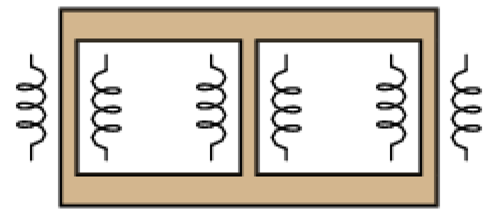


- High voltage transmission to reduce $I^2R$ losses
- Must have heavy windings to withstand $P=EI$
- If load increases excessively then circuit breakers open for transformer protection




3-phase connection is important

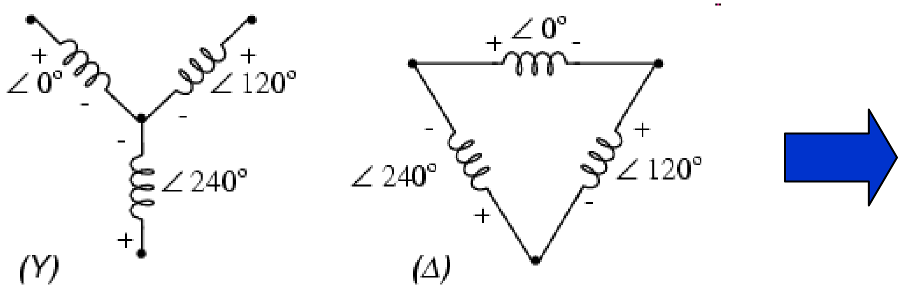
# 3-phase Transformer Connections




- *3-ph t/r core has three sets of windings.*
- P & S windings will be connected in either Δ or Y configurations
- Y connections provide the opportunity for multiple voltages
- Δ connections enjoy a higher level of reliability (if one winding fails open, the other two can still maintain full line voltages to the load).

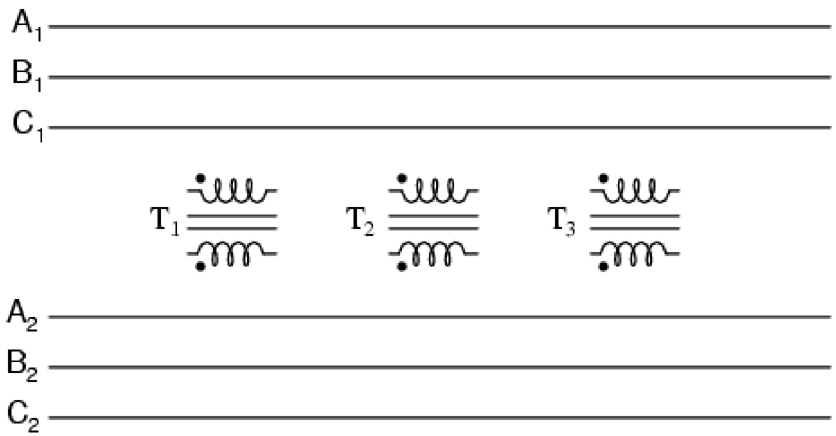
| **Primary** | - | **Secondary** |
|---|---|---|
| Y | - | Y |
| Y | - | Δ |
| Δ | - | Y |
| Δ | - | Δ |

Extremely Important – Proper Winding Phasing:

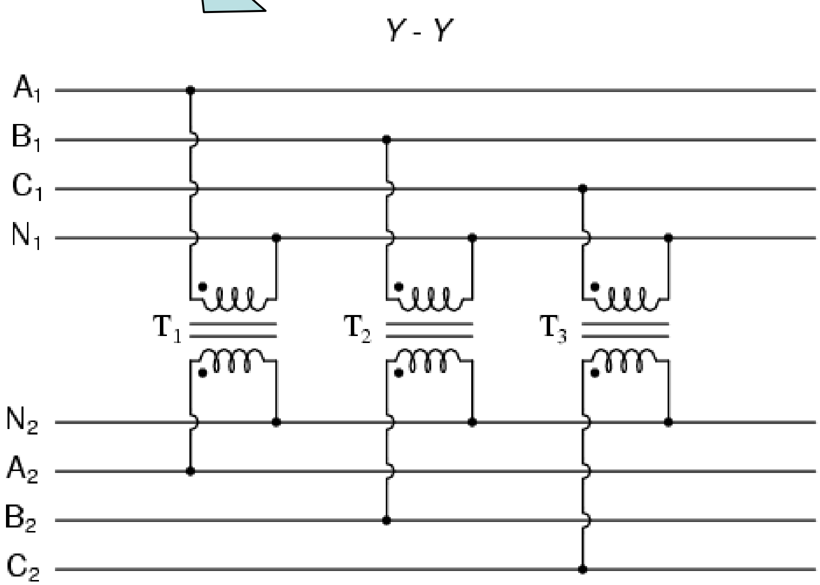


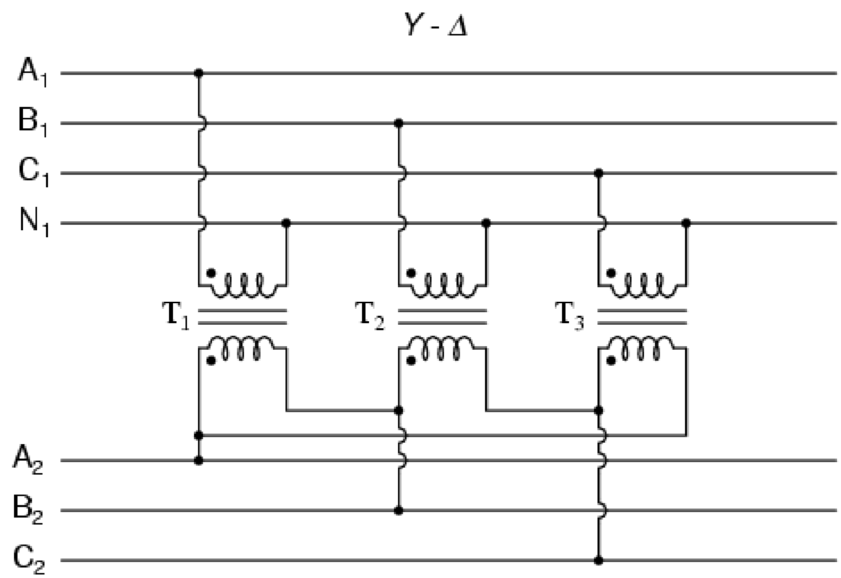

- *Y: The center must tie all "-" or "+"*
- Δ: *The winding polarities must stack in a complementary manner ( + to -).*

# 3-phase Transformer Connections




Computer software may be used for complex multiple winding connections



# What Happens with Wrong Winding?

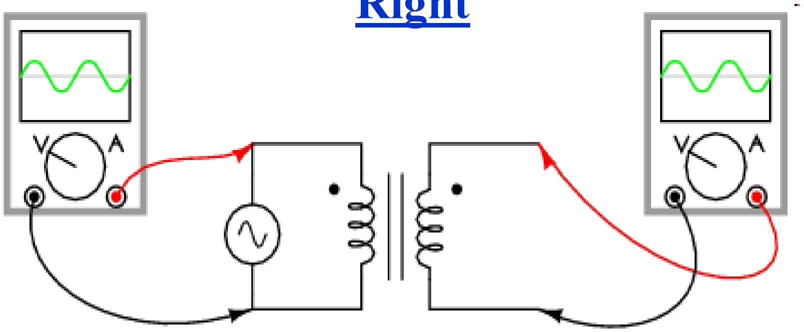
→ Students must understand the effect of wrong winding connections

→ Catastrophic? Harmful? Brownout?

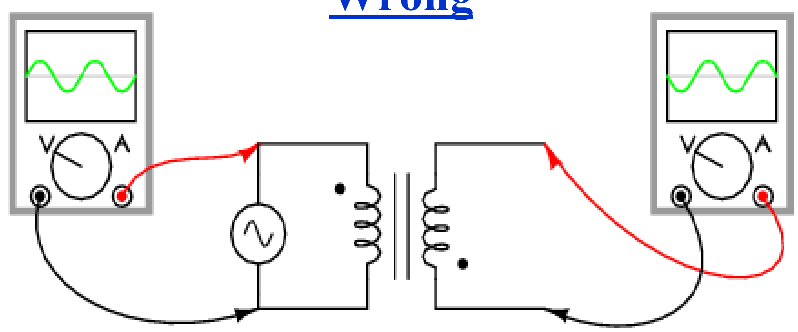
**Not really!**

Take a single-phase example:

**Right**

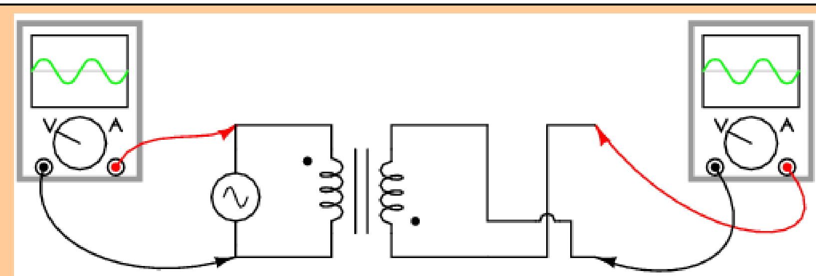



**Wrong**




Look at the oscilloscopes: Phase reverses by 180 deg

Changing it is easy as well →

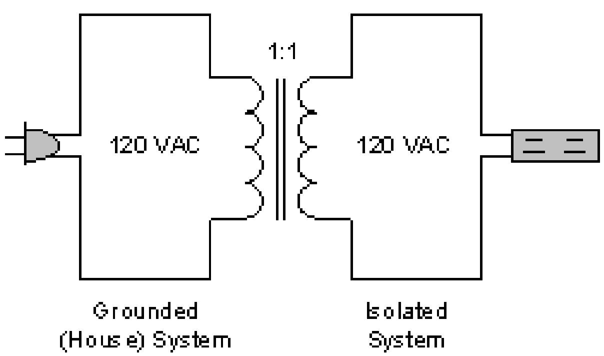


# Distribution Transformer

- Converts higher voltage (usually 11-22-33kV) to a lower voltage (250 or 433V) with same frequency
- Pole-mounted, ground-mounted, integrated transformer substation

# Isolation Transformer

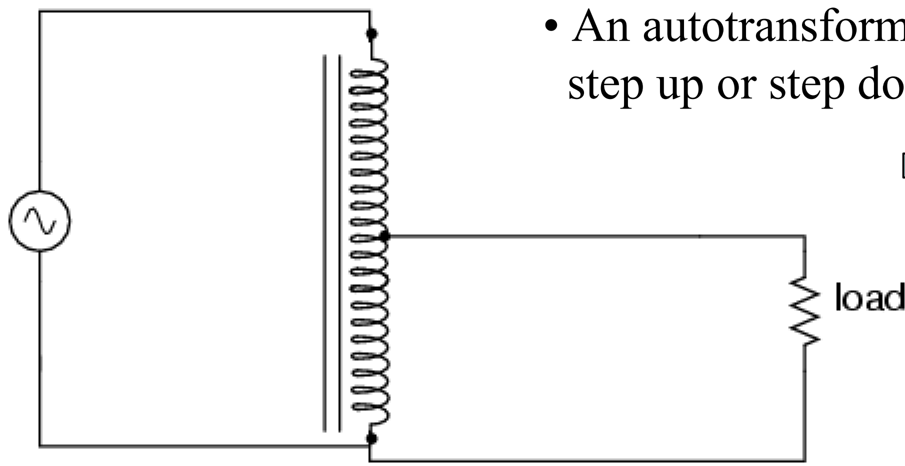
- Capacitance from a winding to any nearby conductor - such as other windings, the core, and the chassis
- This capacitive coupling mechanism can carry high frequency noise on the input primary to the output secondary windings or vice versa.
- Isolation transformers are designed to minimize this coupling




Turn ratio 1:1 as no voltage boost/buck is required

# Auto-Transformer

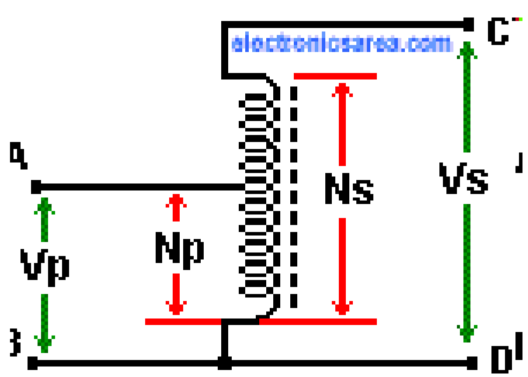
Autotransformer

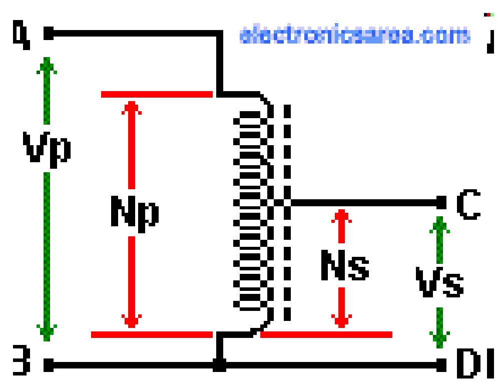



- An autotransformer is a **single**, tapped inductor coil used to step up or step down voltage like a transformer (cheap)

⇨ No electrical isolation, however.

Main points: 1. Operation
2. Phasor Diagram
3. Pros, Cons




**Boosting** and **Bucking** totally depend on **taps**

- Applications: On long rural power distribution lines, special autotransformers with automatic tap-changing equipment are inserted as **voltage regulators** (VARIAC)

# Transformer Tests

Laboratory tests have to be set up so that students can compute the **equivalent circuit** of a real transformer

- **Open circuit test**: to determine no-load iron loss

Hysteresis: *Steinmetz's* emperical relation
Eddy current: square of frequency

$$W_{iron} = W_h + W_e = PB_{\max}{}^{1.6} f^2 + QB_{\max}{}^2 f^2$$

- **Short circuit test**: to determine leakage reactance, equivalent impedance, copper loss, voltage regulation

→ Lab sessions must be integrated with group projects for calculations

→ Can be a part of design project as well

# Interesting Class Project Problems

## Topic # 1: Phase Shift Control

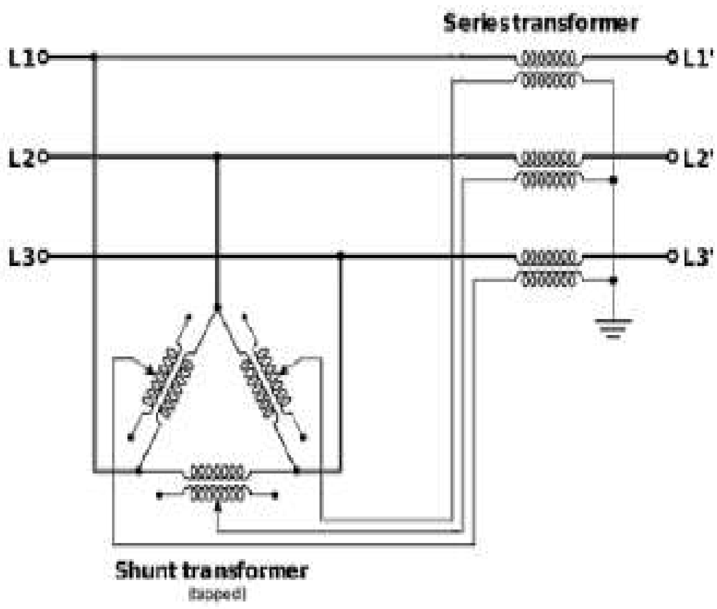
• Transformers can be used for phase shifting between two generators to vary active power flow in a line

• Direct PST's phase shift is obtained by connecting the windings appropriately.

$$P = \frac{E_1 E_2}{x_e} \sin(\delta + \alpha)$$

→ Some interesting things students can explore:

* Different connections and different resulting
* How does the power angle curve change?
* Any effect on voltage amplitude?
* Does this affect the PV curve?




## Topic # 2: Load Balancing

## Topic # 3: Voltage Optimization & Regulation

# Conclusions

- By the end of the course, students should understand:

Transformers: what and why

Equivalent circuit, vector diagrams

Loss, Efficiency, how to calculate them?

3-ph connection, phase shift, variac

* Study of transformers is important, but is tough and dry
* Visual aids can be helpful – pictures, phasors, graphics
* Interesting projects can be useful as well
* Should not be restricted to dry mathematics
* Practical lab tests are **essential**