Autotransformer

- A conventional two-winding transformer can be changed to an autotransformer by connecting its two coils in series (note: four different ways to connect).
- The connection may use a sliding contact to providing variable output voltage.

An autotransformer can be created by starting with a two winding transformer and then physically connecting the primary and secondary windings.

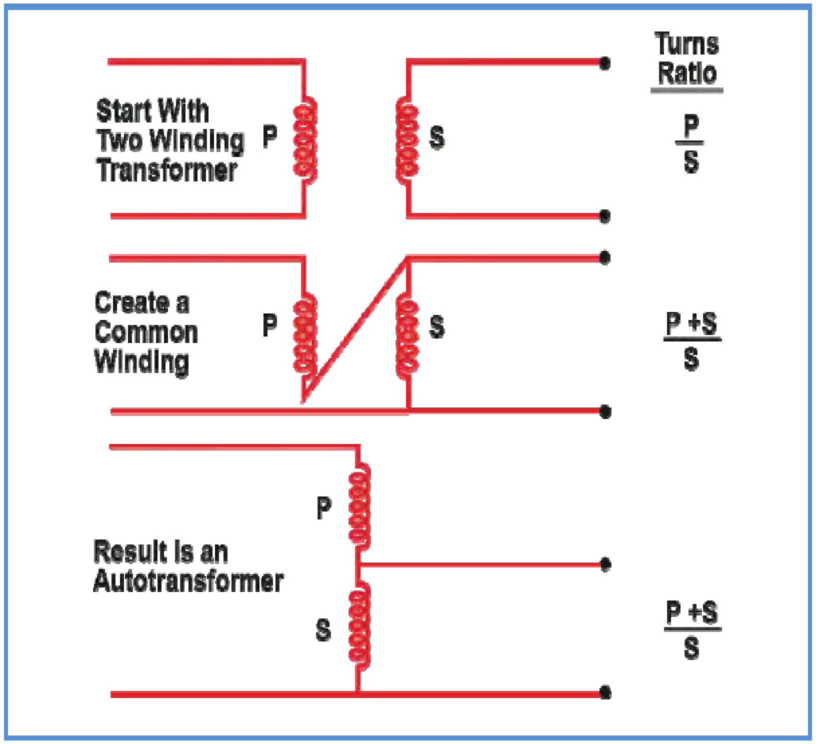
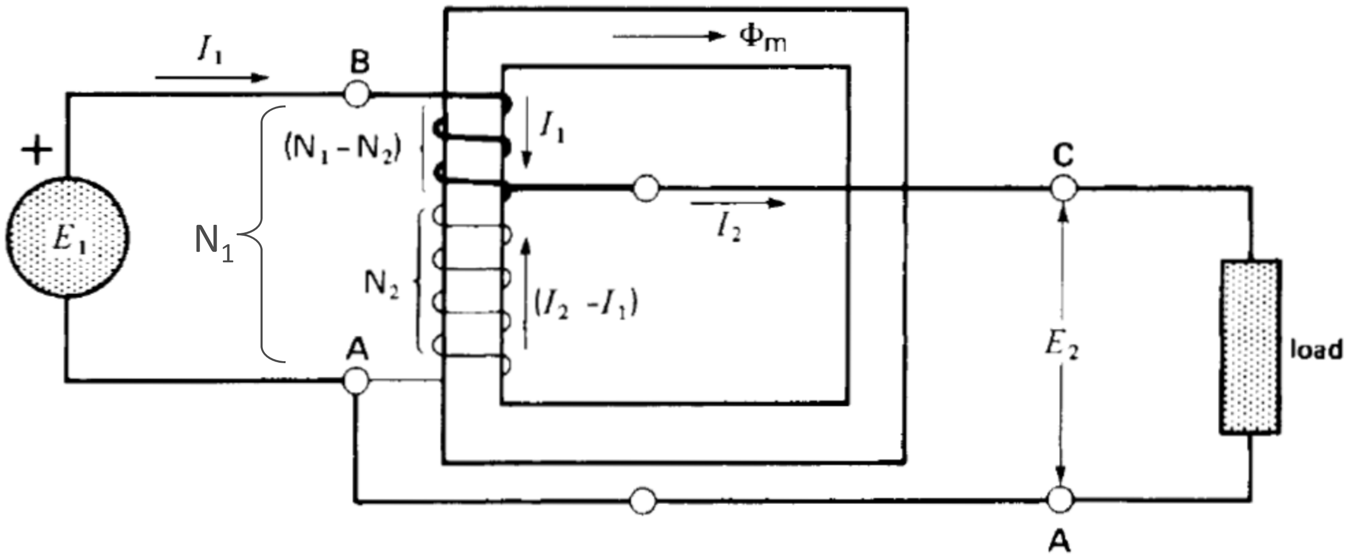


Figure 2-80. Autotransformer Evolution From a Two-Winding Transformer

(Source: EPRI Power System Dynamic Tutorial)

20MVA (115/69kV) McGraw-Edison Substation Auto-Transformer (Y-Y) (Source: http://www.tucsontransformer.com)



- The primary and secondary windings have a common terminal A, and hence are not isolated from each other

$E_2/E_1 = E_{CA}/E_{BA} = N_2/N_1$ (There is always $N_1 > N_2$)

$I_1 N_1 = I_2 N_2 \Leftrightarrow \quad I_1(N_1 - N_2) = (I_2 - I_1) N_2$

$E_1 I_1 = E_2 I_2$

- An autotransformer has a smaller size (or equivalently, a higher kVA rating for the same size) but loses insulation between primary and secondary windings

Conventional transformer connected as an autotransformer (Example 11-2)

- Reconnect the transformer to obtain
  - 600V / 480V
  - 600V / 720V
  - 120V / 480V
  - 120V / 720V

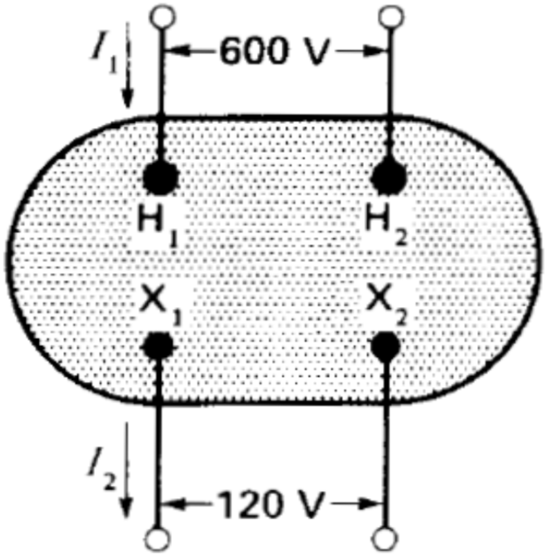
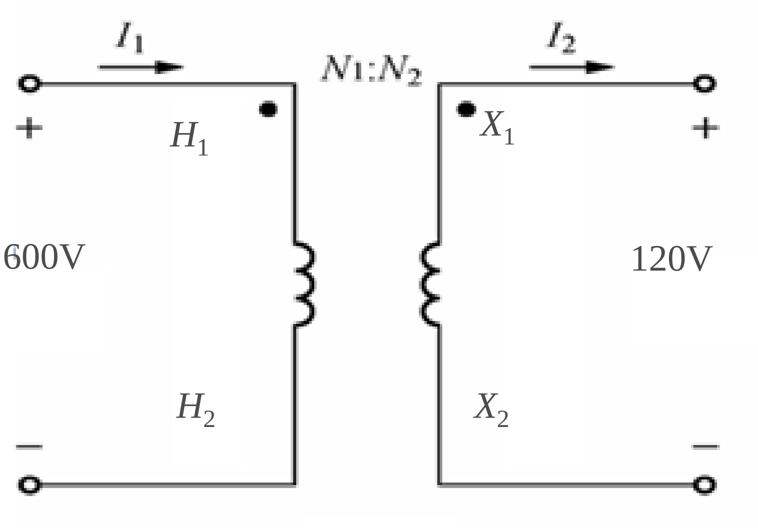
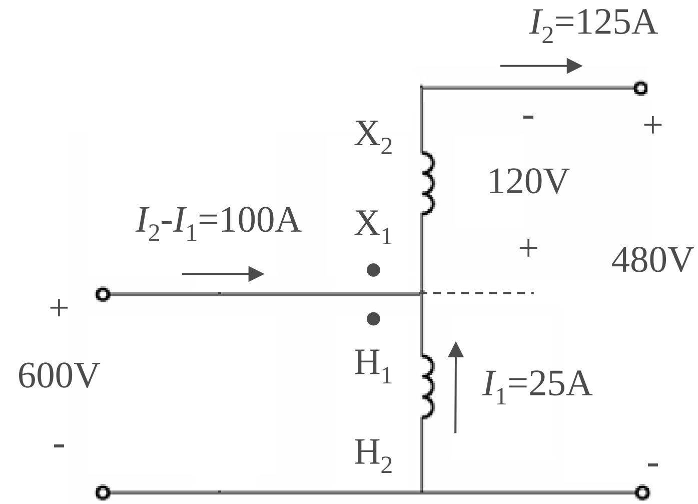


Figure 11.6
Standard 15 kVA, 600 V/120 V transformer.

- I_1=15000/600=25A
- I_2=15000/120=125A

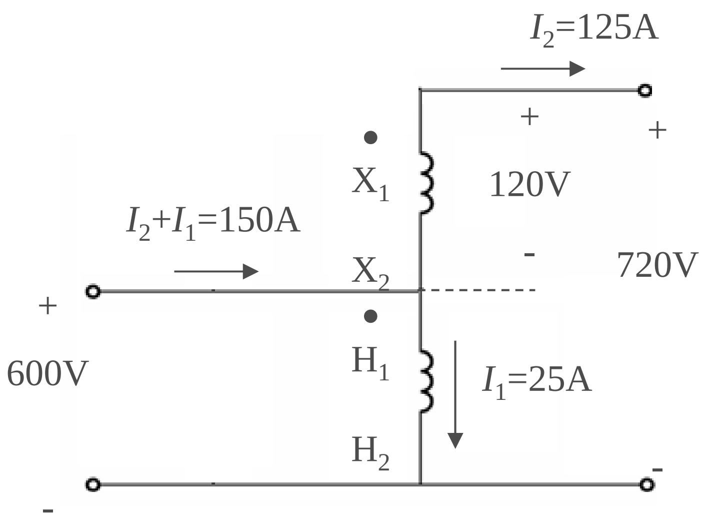
When a transformer connects a source (on the primary side) with a load (on the secondary side), it is the load (current flows into terminal +) of the primary circuit and is the source (current flows out of terminal +) of the secondary circuit, so **two winding currents (I_1 and I_2) have opposite directions**.





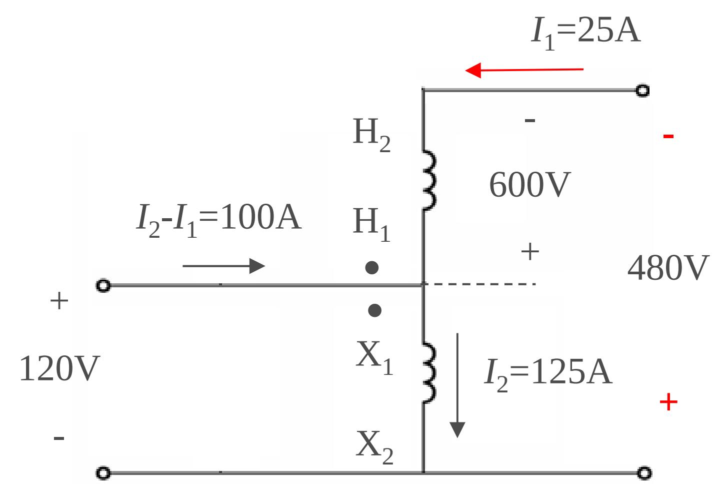
$|S_i|$=600×100=60kVA

$|S_o|$=480×125=60kVA



$|S_i|$=600×150=90kVA

$|S_o|$=720×125=90kVA



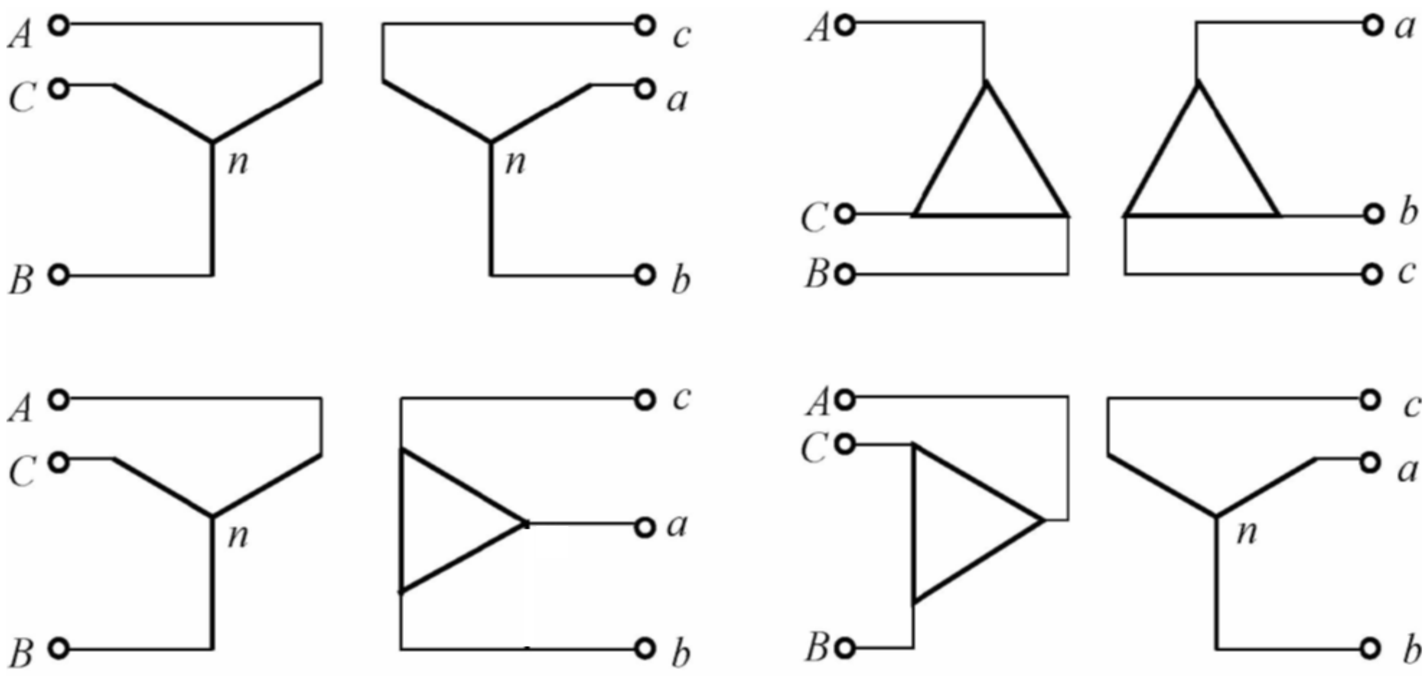
$|S_i|$=120×100=12kVA

$|S_o|$=480×25 =12kVA

The maximum apparent power $|S_{max}|=\max(|E_1|,|E_2|)\times(|I_1|+|I_2|)=(|E_1|+|E_2|)\times\max(|I_1|,|I_2|)$

Three-Phase Transformers

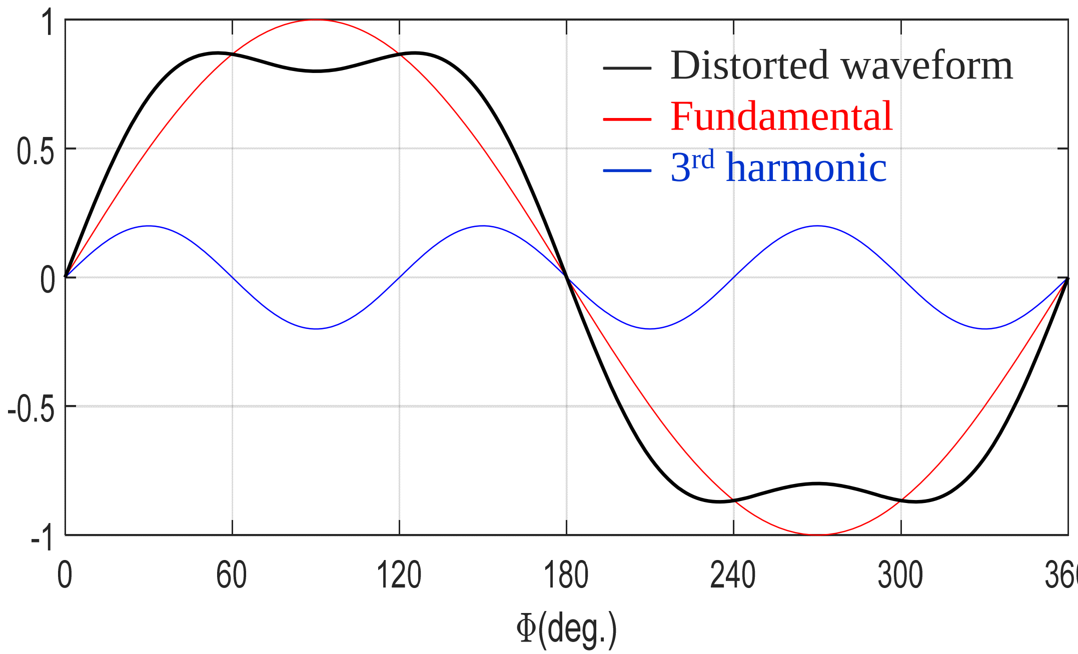
- A bank of three single-phase transformers connected in Y or Δ configurations
  - Four possible combinations: Y-Y, Δ-Δ, Y-Δ and Δ-Y

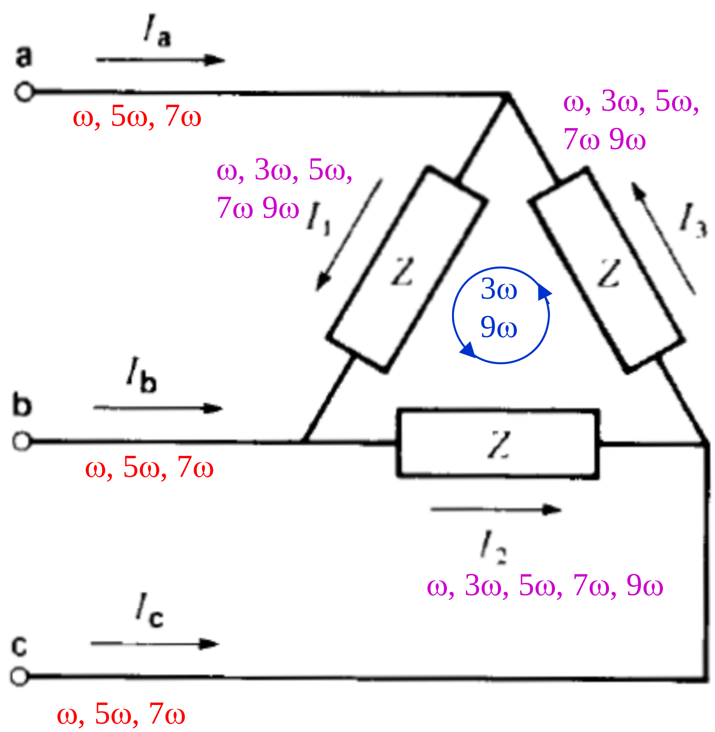


  - Y: lower insulation costs, with neutral for grounding, 3rd harmonics
  - Δ: more insulation costs, no neutral, no 3rd harmonics

3rd harmonics problem with three-phase transformers

- A △ configuration provides a closed path for 3rd harmonics, or in other words, all triple harmonics are trapped in the △ loop.
  - The 120° phase difference between the fundamental harmonic of I_1 an I_2 and I_3 becomes 360° (in phase) for the 3rd harmonic
  - Then by KCL, $I_a(3\omega)=I_1(3\omega)-I_3(3\omega)=0$; also $I_b(3\omega)=I_c(3\omega)=0$





Three-phase transformers: Y-Y connection

- No phase shift between the incoming and outgoing line voltages
- Without a Δ configuration to trap the 3rd harmonic, it has seriously distorted voltages due to the 3rd harmonics.
- Two solutions:
  - Ground the neutrals of the primary winding and the source
  - Provide each transformer with a tertiary winding, and connect 3 tertiary windings in delta

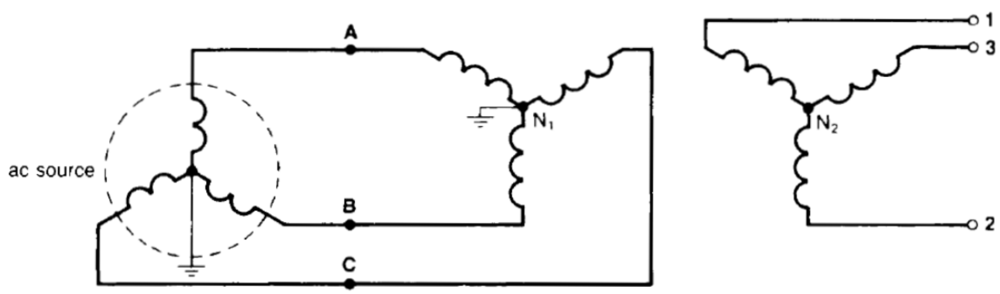


Figure 12.6
Wye-wye connection with neutral of the primary connected to the neutral of the source.

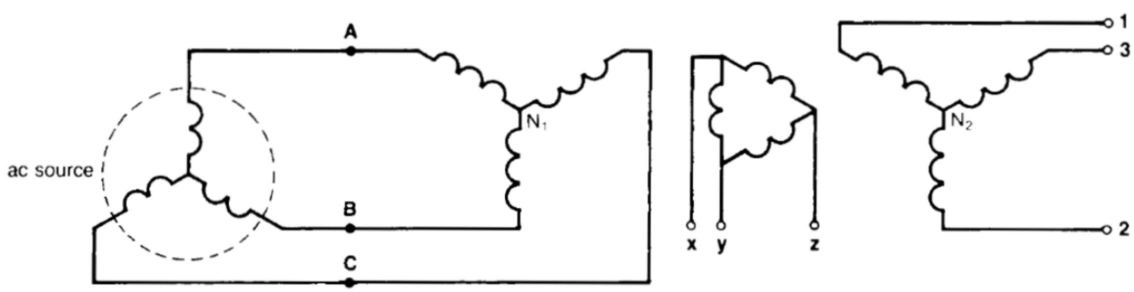


Figure 12.7
Wye-wye connection using a tertiary winding.

Three-phase transformers: Δ-Δ connection

- Each transformer, considered alone, acts as if it were placed in a single-phase circuit.
- Because E_{H1H2} and E_{X1X2} are in phase for each single transformer, line voltages E_{AB} with E_{12}, E_{BC} with E_{23}, and E_{CA} with E_{31} are in phase.
- A balanced three-phase load produces balanced line currents in line 1-2-3 and lines A-B-C
- The power rating is 3x of a single transformer.
- Under maintenance or emergency conditions, one transformer may be absent (i.e. **open-delta connection**, whose power rating becomes 86.7% of the original; see Exp 12-3)

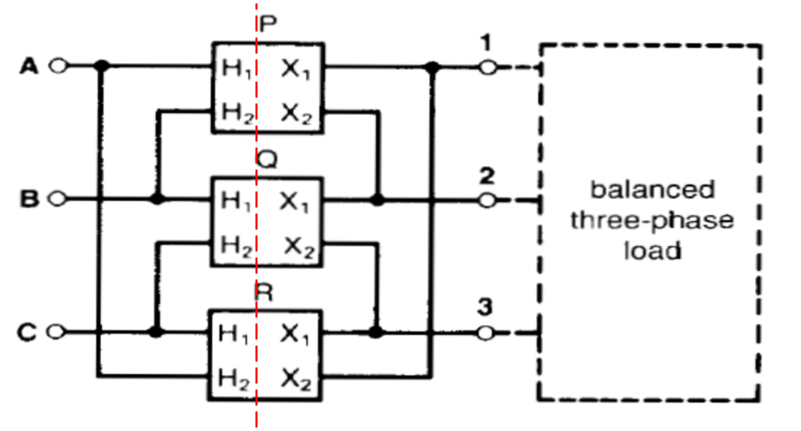
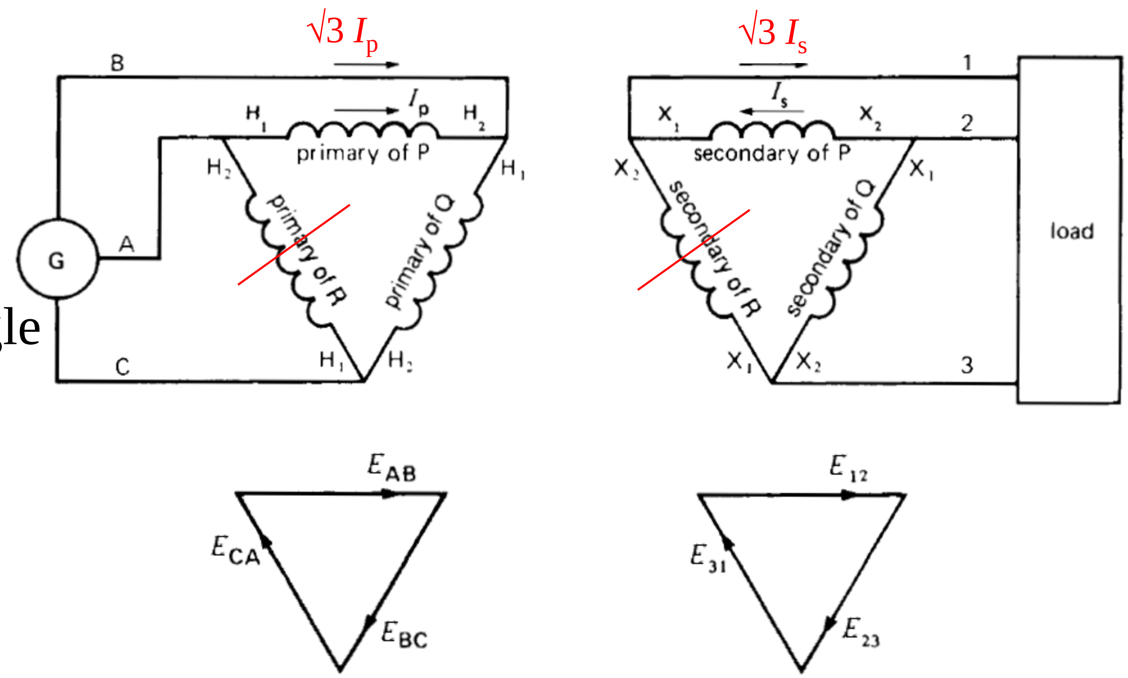


Figure 12.1
Delta-delta connection of three single-phase transformers. The incoming lines (source) are A, B, C and the outgoing lines (load) are 1, 2, 3.



Three-phase transformers: Δ-Y (or Y-Δ) connection

- X_2 terminals of 3 secondary windings are connected to a common neutral N.
- Because E_{H1H2} and E_{X1X2} are in phase for each single transformer, E_{AB} with E_{1N}, E_{BC} with E_{2N}, and E_{CA} with E_{3N} are in phase.
- There is a 30° phase shift between the line voltages of the incoming (E_{AB}) and outgoing (E_{12}) lines
- Δ-Y is commonly used for voltage step-up transformers while Y-Δ is commonly used for voltage step-down transformers

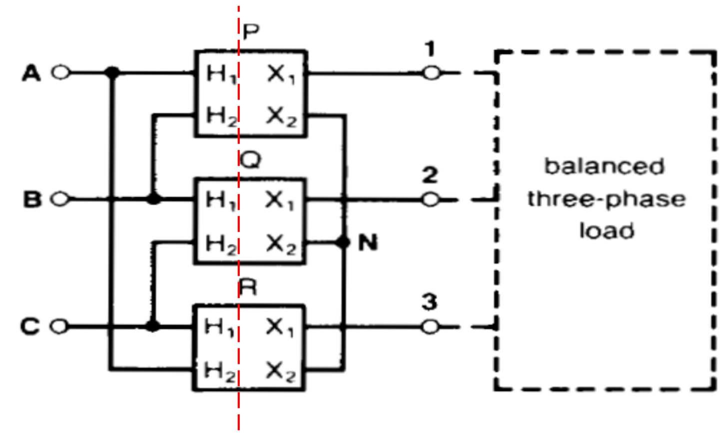
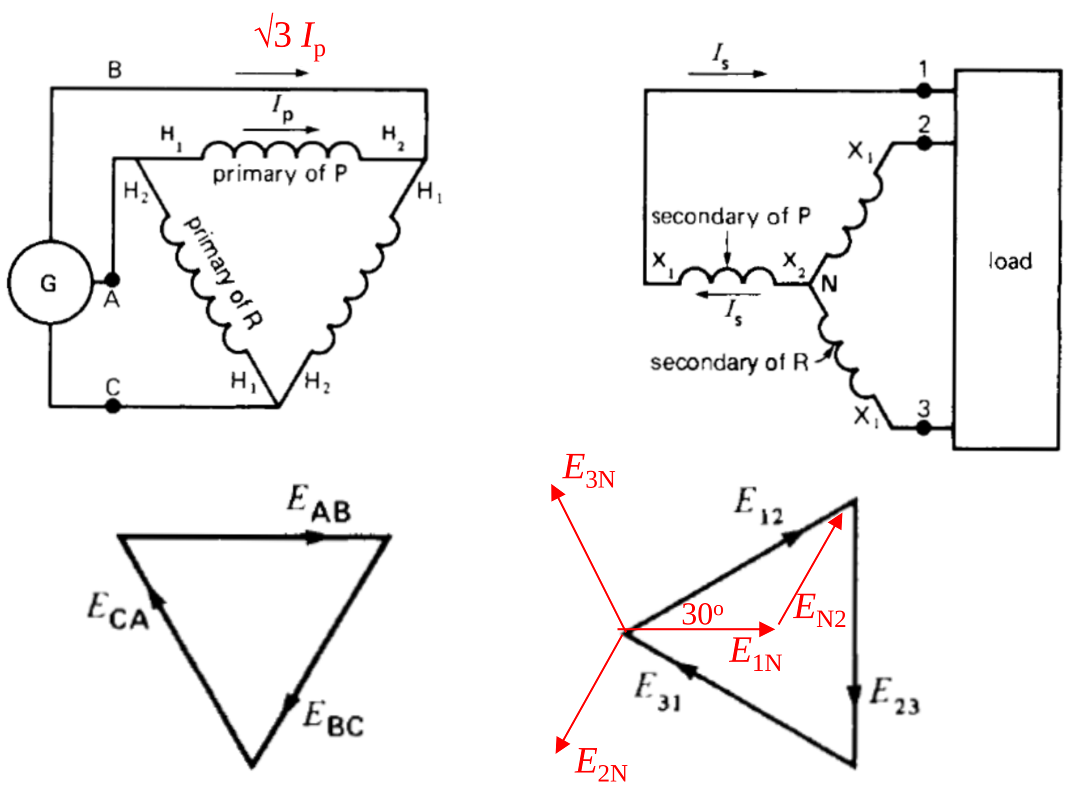


Figure 12.3
Delta-wye connection of three single-phase transformers.



Calculations involving 3-phase transformers

- For any 3-phase transformer bank, assume that the primary and secondary windings are both connected in Y configuration (if not, transform it to Y by $|Z_Y|=|Z_\Delta|/3$)

- Consider only one transformer (single phase) of the assumed Y-Y transformer bank
  - Its primary and secondary voltages are both the line-to-neutral voltages of the incoming and outgoing lines
  - Its nominal power rating and load are 1/3 of the 3-phase transformer bank

Examples 12-1, 12-2, 12-3, 12-6 & 12-7

Phase-shifting Principle

- A 3-phase system can easily shift the phase angle of a voltage to create 2-, 6-, and 12-phase systems used in power electronic converters and controllers
- Phase shifting (performed by phase-shifting transformers) is also used in power flow control over long transmission lines

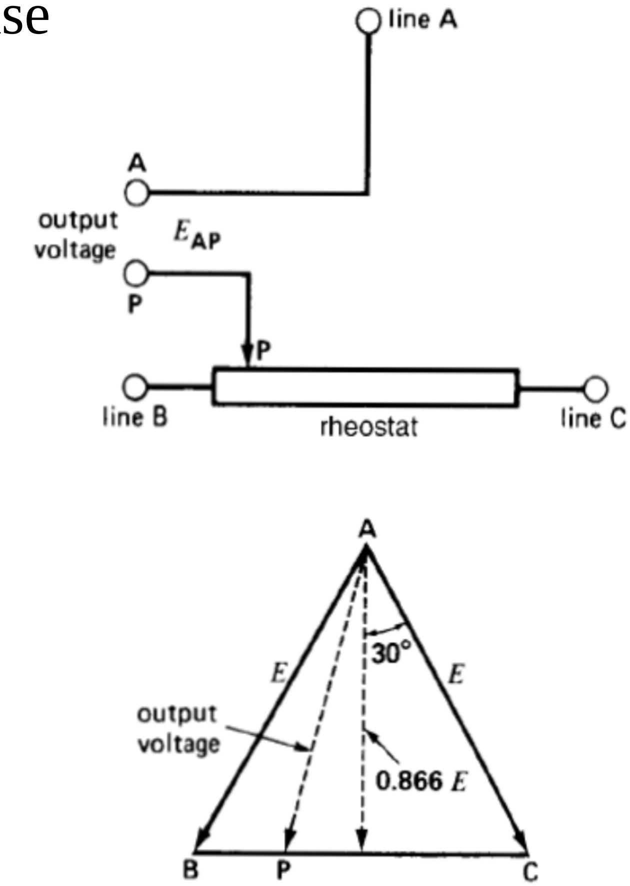
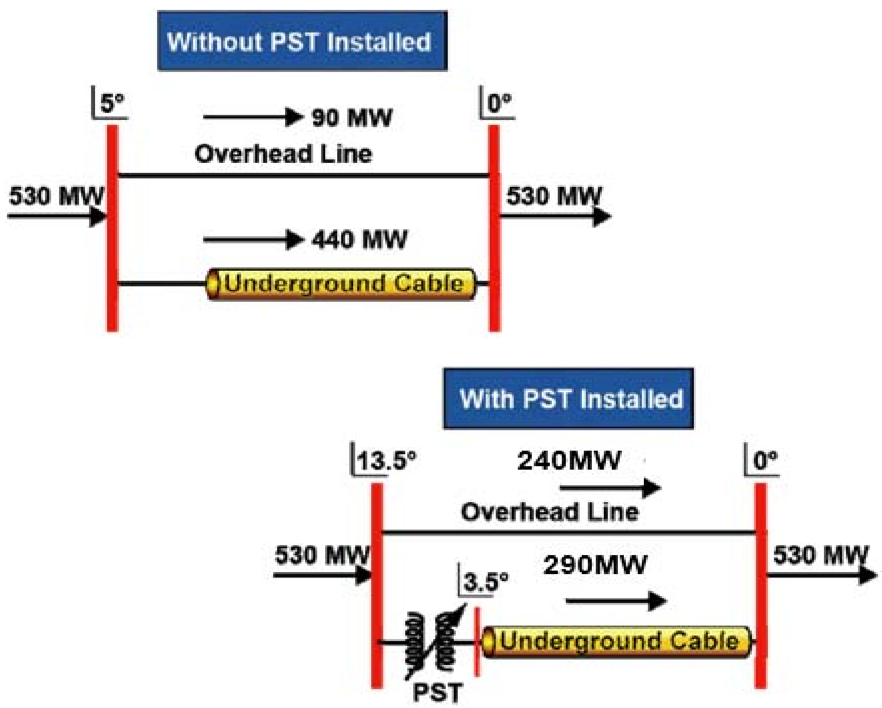
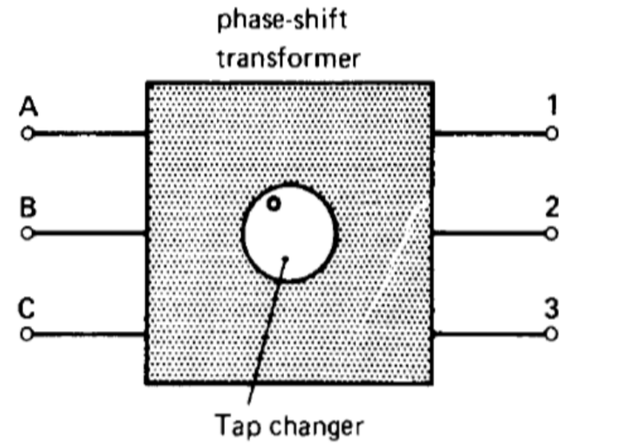


Figure 12.12
Voltage E_{AP} can be phase-shifted with respect to E_{AC} by means of a potentiometer.



Phase-shifting transformers

- A special type of 3-phase autotransformer that shits the phase angle between the incoming and outgoing lines without changing the voltage ratio.
- Twist all incoming line voltages by angle α (0~±20°) without changing their magnitudes



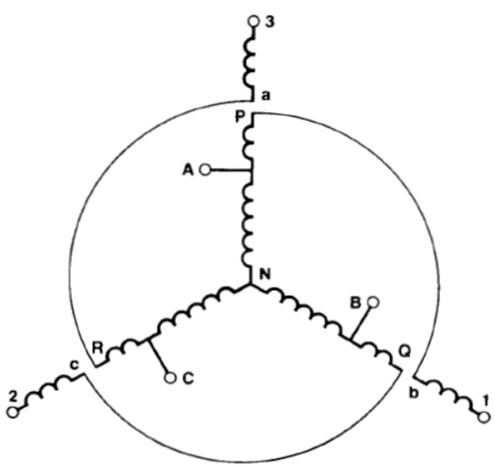
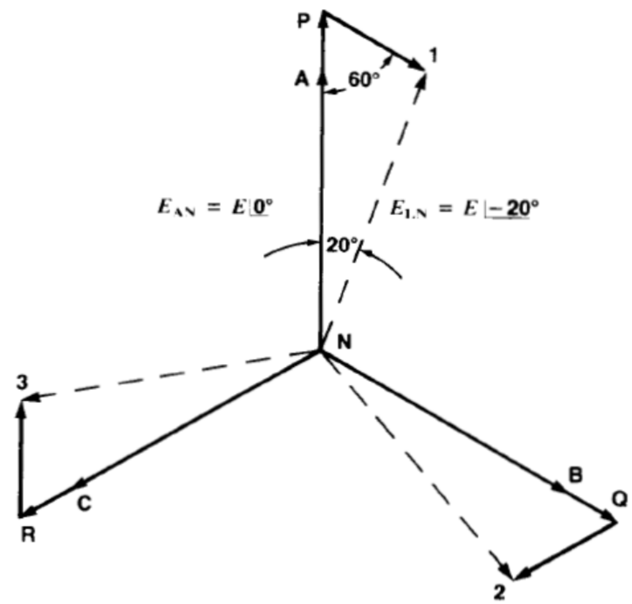


Figure 12.18b
Schematic diagram of the transformer in Fig. 12.18a.



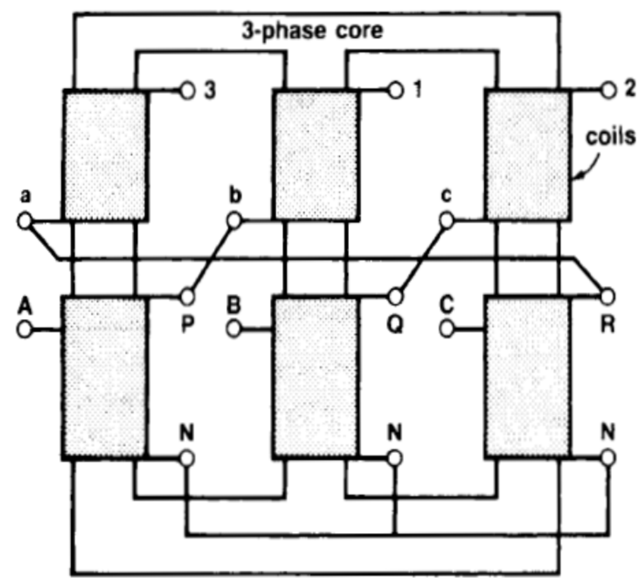


Figure 12.18a
Construction of a 3-phase-shift transformer. The incoming terminals are A, B, C; the outgoing terminals are 1, 2, 3.

Voltage Transformers and Current Transformers

- Voltage transformers (VTs), also called potential transformers (PTs), are installed on HV lines to measure line-to-neutral voltage

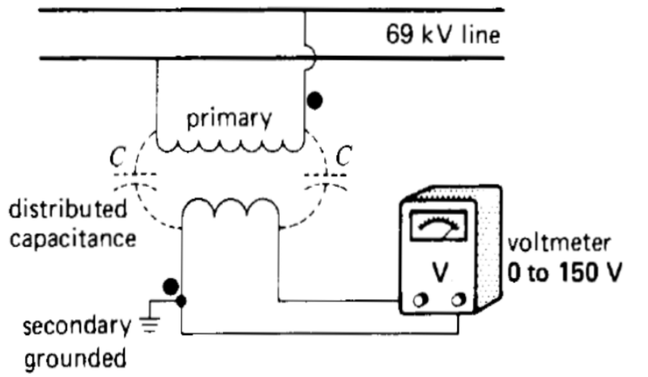
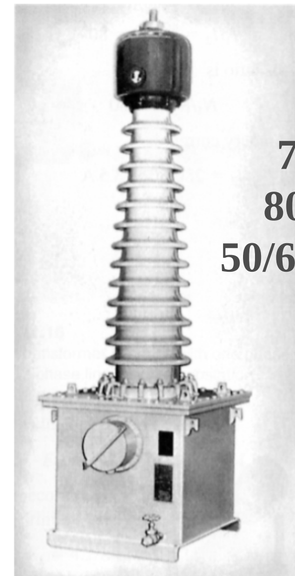


Figure 11.11
Potential transformer installed on a 69 kV line. Note the distributed capacitance between the windings.



7kVA
80.5kV
50/60Hz PT

- Current transformers (CTs) are used to measure or monitor the current in a line for system measurement and protection

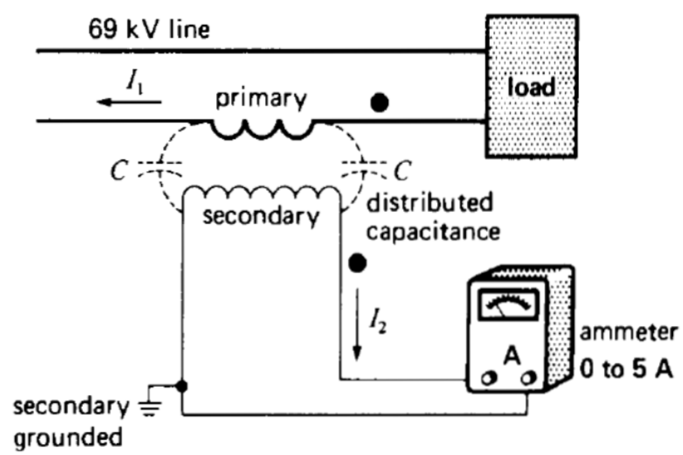


Figure 11.13
Current transformer installed on a 69 kV line.

5kVA,
100A/5A
60Hz CT