Chapter 12: Three-Phase Transformers

Introduction

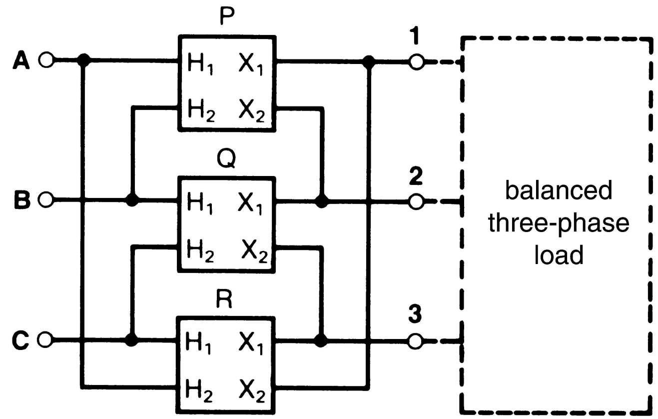
- In the operation of power systems, transformers are required to change the voltage levels throughout the network
  - three-phase circuits use three-phase transformers
    - can be achieved by using a bank of three single-phase transformers
    - may be a 3-phase unit having three primary windings and three secondary windings on a 3-legged core
  - using a bank of three single phase transformers, the windings may be connected in a variety of ways
    - the primary side may be connected in a wye or delta configuration independent of the secondary connection
    - the secondary side may be connected in a wye or delta configuration independent of the primary connection

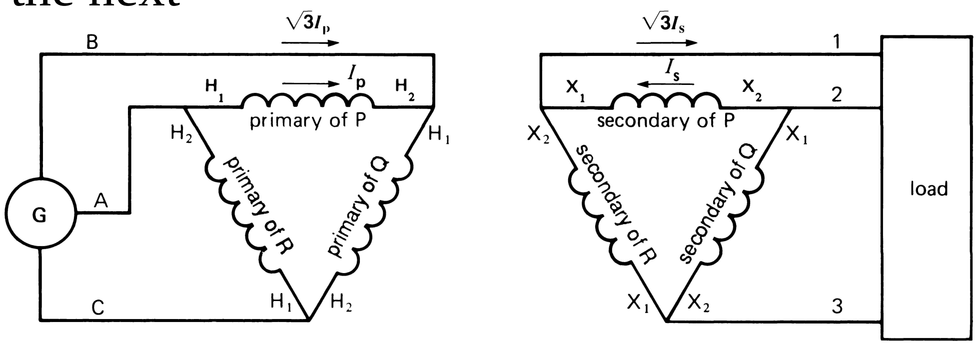
Transformer Banks

- 3-phase transformer banks can be analyzed using simplifying assumptions
  - excitation currents are negligible
  - winding impedances are negligible
  - total apparent input power equals the total apparent output power
- Single-phase transformers connected into a 3-phase bank
  - retain all basic single-phase properties
  - individual voltage and current transformations are based on the single-phase turns ratio
  - phase shift between primary and secondary is zero
- 3-phase transformer banks can introduce a phase shift between the three-phase primary and the three-phase secondary
  - function of the primary and secondary winding connections

Delta-Delta Connection

- Three single-phase transformers connected delta-delta
  - the H_1 terminal of each transformer is connected to the H_2 terminal of the next transformer
  - the X_1 terminal of each transformer is connected to the X_2 terminal of the next transformer
  - the primary-side line voltage is transformed to the secondary-side line voltage
  - the primary and secondary voltages and currents are in-phase



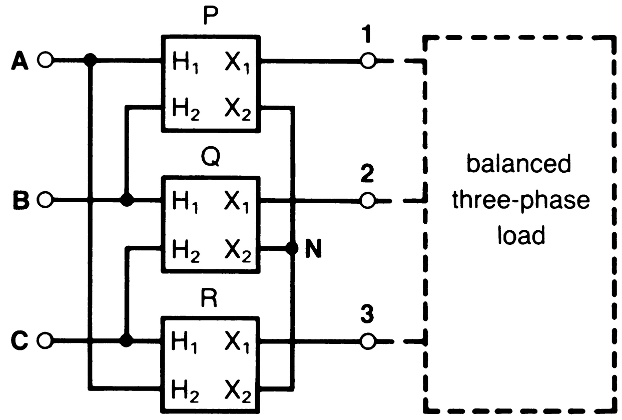


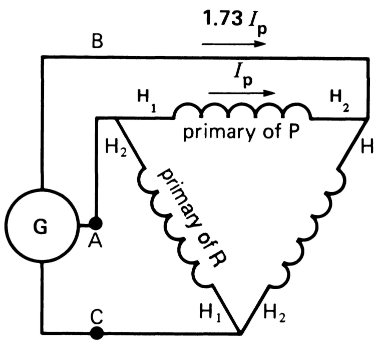
Delta-Delta Connection

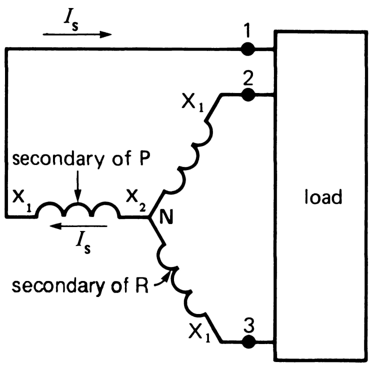
- Example
  - three single-phase transformers are connected in delta-delta configuration to step down a line voltage of 138 kV to 4160 V to supply power to a manufacturing plant
  - the plant draws 21 MW at 0.86 power factor lagging
  - calculate
    - the apparent power drawn by the plant
    - currents in the HV lines and the LV lines
    - current in the primary and secondary windings of each transformer
    - the load carried by each transformer

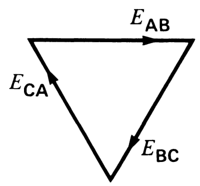
Delta-Wye Connection

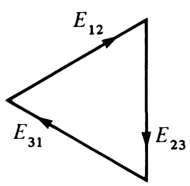
- Three single-phase transformers connected delta-wye
  - the H_1 terminal of each transformer is connected to the H_2 terminal of the next transformer
  - the X_2 terminals of all transformers are connected together to form a neutral terminal
  - the primary-side line voltage is transformed to the secondary-side phase voltage
  - the delta-wye connection produces a 30° phase shift between the primary and secondary voltages and currents





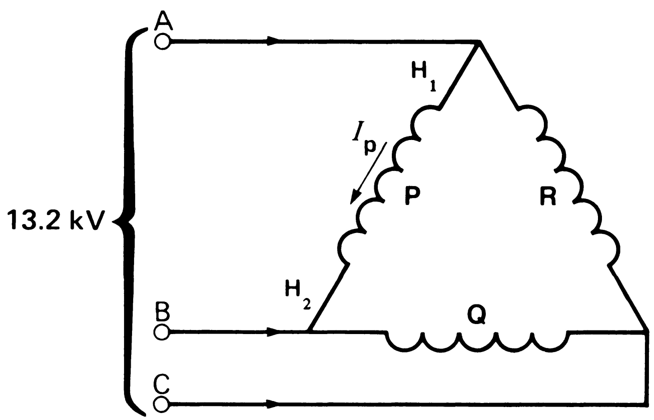


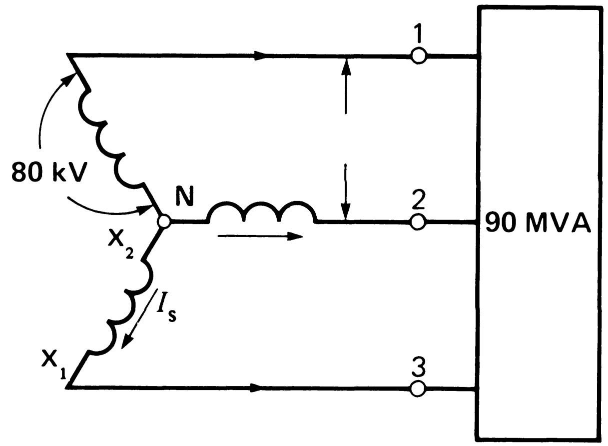




Delta-Wye Connection

- Example
  - three single-phase step-up transformers rated at 40 MVA, 13.2 kV / 80 kV are connected in a delta-wye configuration to a 13.2 kV transmission line
  - the 80 kV load is 90 MVA
  - calculate
    - the secondary line voltage
    - the currents in each winding of the transformer
    - the line currents in the LV and HV transmission lines



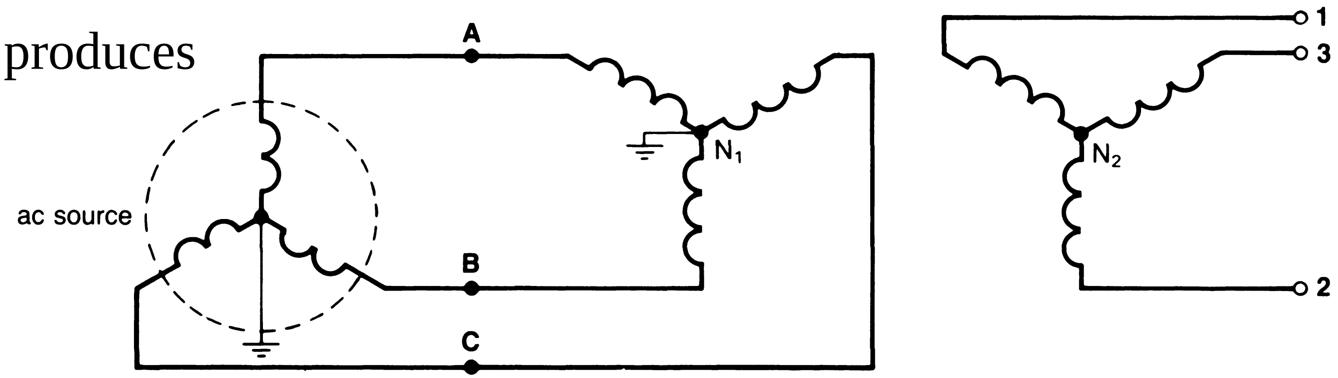


Wye-Delta Connection

- The currents in a wye-delta connection are identical to those in the delta-wye connection
  - the primary and secondary connections are simply interchanged
  - the H_2 terminals of all transformers are connected together to form a neutral terminal
  - the X_1 terminal of each transformer is connected to the X_2 terminal of the next transformer
- Again, the connection results in a 30° phase shift between the primary and secondary voltages and currents
  - the primary-side phase voltage is transformed to the secondary-side line voltage

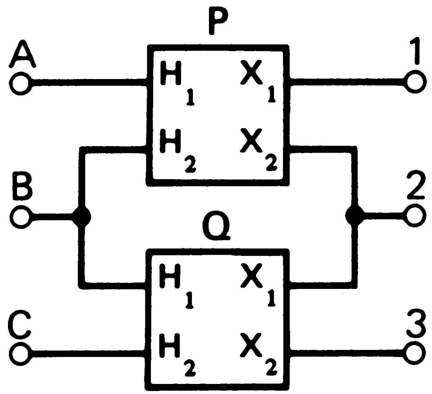
Wye-Wye Connection

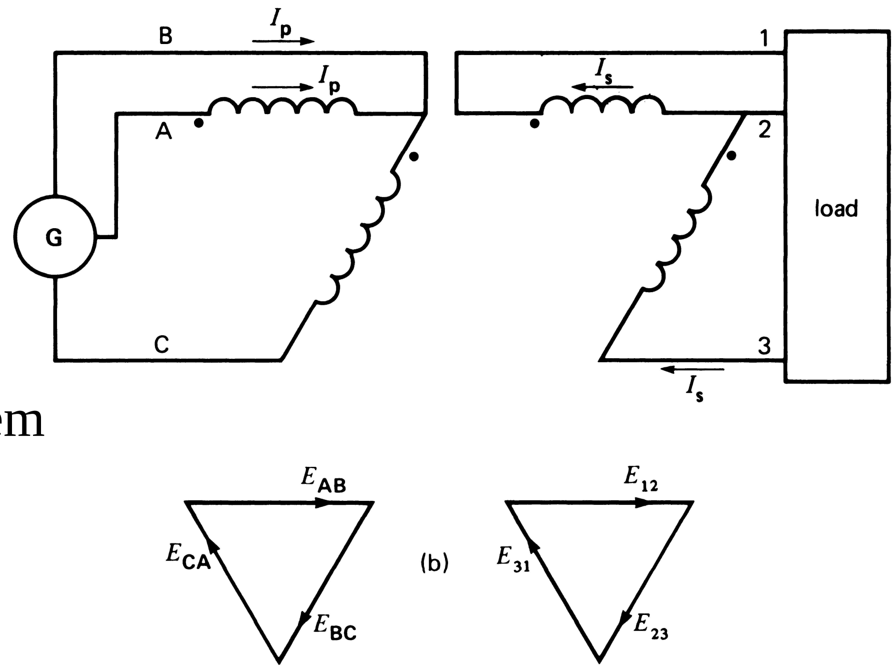
- Three single-phase transformers connected wye-wye
  - the H_2 terminals of all transformers are connected together to form a neutral terminal
  - the X_2 terminals of all transformers are connected together to form a neutral terminal
  - the primary-side phase voltage is transformed to the secondary-side phase voltage
  - the neutral terminal of the primary side of the transformer must be connected back to the source with a low impedance path to avoid secondary voltage magnitude distortion with unbalanced loads
  - the connection produces no phase shifts



Open-Delta Connection

- It is possible to transform the voltage of a 3-phase system using only 2 transformers
  - open-delta arrangement is identical to a delta-delta connection, less one transformer
  - limited use due to a 86.6% reduction in the installed power capability
    - two 50 kVA transformers could carry 100 kVA, but limited to 86.6 kVA in an open-delta connection
    - used in emergency conditions
    - used in metering of power system voltages





Open-Delta Connection

- Example
  - two single-phase 150 kVA, 7200 V / 600 V transformers are connected in open-delta
  - calculate the maximum 3-phase load they can carry

Three-phase Transformers

- A transformer bank composed of three single-phase units may be replaced by one 3-phase transformer
  - the magnetic core has three flux-carrying legs
    - two yokes, bottom and top, couple the flux of the three legs
    - the sum of the three fluxes equals zero
  - each leg contains the primary and secondary windings of one of the phases
  - the windings are connected delta or wye, internal to the transformer tank
  - only six terminals are brought out of the tank

Circuit Analysis

- The behavior of a 3-phase transformer bank is analyzed in the same way as for a single-phase unit
  - assume that both the primary and secondary windings are connected in wye configuration
  - consider only one transformer
  - the primary voltage is the line-to-neutral voltage, $V_{\mathrm{H1},n}$
  - the secondary voltage is the line-to-neutral voltage, $V_{\mathrm{X1},n}$
  - the nominal power rating is one-third the rating of the bank
  - the load on the secondary is one-third the secondary load on the bank

Circuit Analysis

- Example
  - a 3-phase, 1300 MVA, 24.5 kV / 345 kV, 60 Hz generator step-up transformer has a leakage impedance of 11.5%
    - determine the equivalent circuit of this transformer on a per-phase basis
    - calculate the voltage across the generator terminals when the high voltage side of the transformer delivers 810 MVA at 370 kV with a 0.90 lagging power factor

Three-phase Transformers

- Homework
  - Problems: 12-2, 12-4, 12-6*, 12-8, 12-10

    Note: * problems are a design based problems