## Transformer basics and ratings

A Transformer is two coils of wire that are magnetically coupled.

Transformers are only useful for AC, which is one of the big reasons electrical power is generated and distributed as AC.

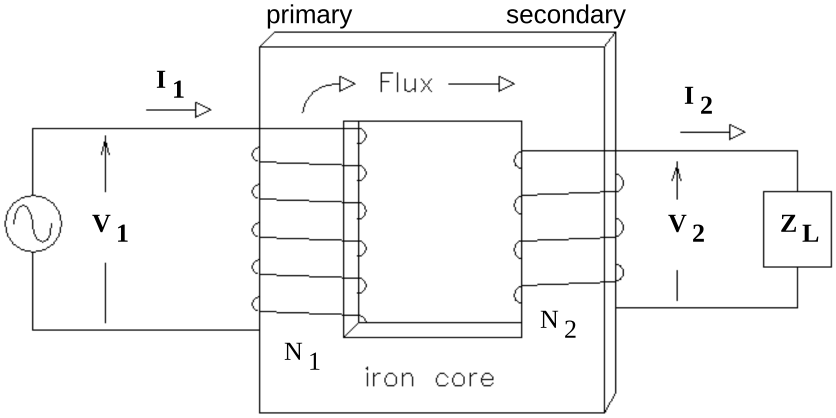
Transformer turns and turns ratios are rarely given, $V_P/V_S$ is much more common where $V_P/V_S$ is the rated primary voltage over rated secondary voltage. Ideally, you may take this to be the same as $N_1/N_2$ although in reality $N_2$ is usually a little bit bigger to make up for losses. Another common way to show the same thing: $V_P : V_S$.

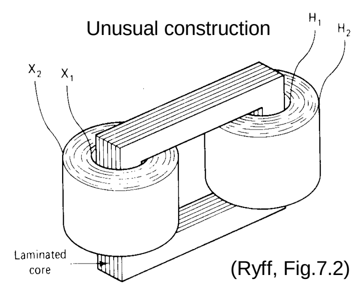
Transformers are rated in VA  Transformer Rating (VA) = (rated V) x (rated I) , on either side.

Don't allow voltages over the rated V, regardless of the actual current.
Don't allow steady-state currents over the rated I, regardless of the actual voltage.
Short-term inrush and startup currents may be higher as long as there's no overheating.

## Ideal Transformers

Iron-core transformer



(Ryff, Fig.7.2)

Ideal: $P_1 = P_2$

power in = power out

Transformation of voltage and current

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

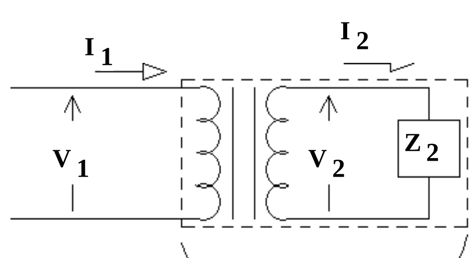
Turns ratio

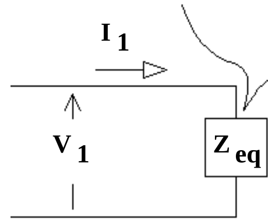
Turns ratio as defined in Chapman text: $a = \frac{N_1}{N_2}$ , same as $N = \frac{N_1}{N_2}$

Note: some other texts define the turns ratio as: $\frac{N_2}{N_1}$

Be careful how you and others use this term

Transformation of impedance



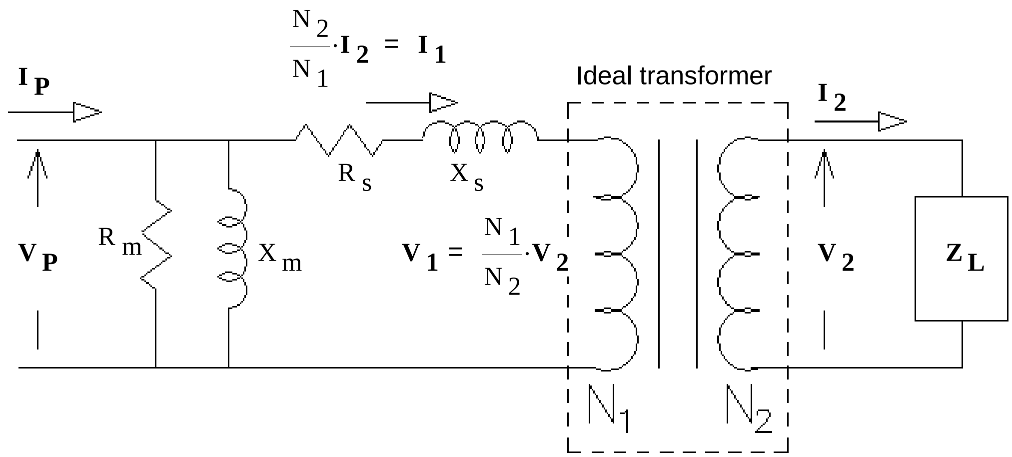

You can replace the entire transformer and load with ($\mathbf{Z_{eq}}$). This "impedance transformation" can be very handy.

$$\mathbf{Z_{eq}} = N^2 \cdot \mathbf{Z_2} = \left(\frac{N_1}{N_2}\right)^2 \cdot \mathbf{Z_2}$$

Transformers can be used for "impedance matching"

This also works the opposite way, to move an impedance from the primary to the secondary, multiply by: $\left(\frac{N_2}{N_1}\right)^2$

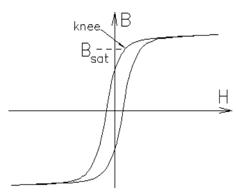
## Model of non-ideal Transformer

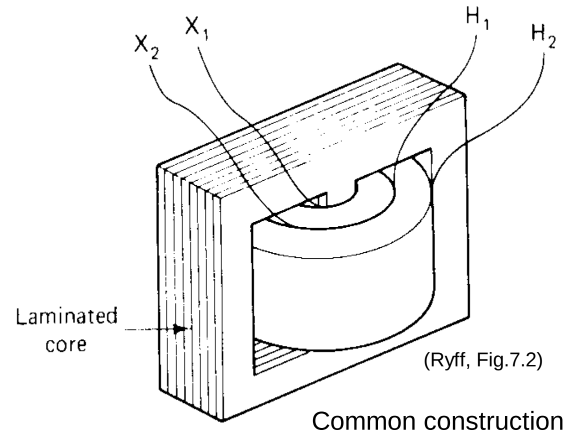



$R_m$ - Core losses

Eddy-current losses - minimized by laminating the core and adding silicon to raise the resistivity

Hysteresis losses - caused by the B-H hysteresis curve




(Ryff, Fig.7.2)

Common construction

(Parts Express)

$X_m$ - basic inductance caused by the need to magnetize the core

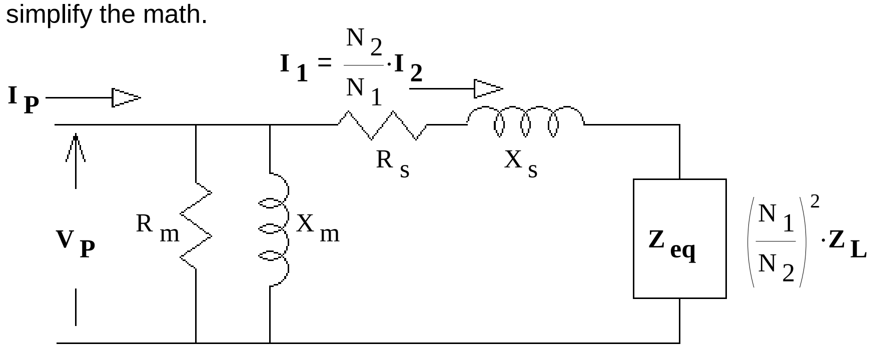
$R_s$ - Winding resistance (copper) losses

$X_s$ - Reactance caused by flux leakage (leakage reactance)

Actually, a more accurate model would have $R_m$ and $X_m$ to the right of $R_s$ and $X_s$ because the magnetization current still has to pass through the windings, but this model is simpler to work with and accurate enough.

Move the load impedance to further simplify the math.

Note: $\mathbf{I_P}$ can be slightly larger than the rated current to makeup for losses.




Typical calculations

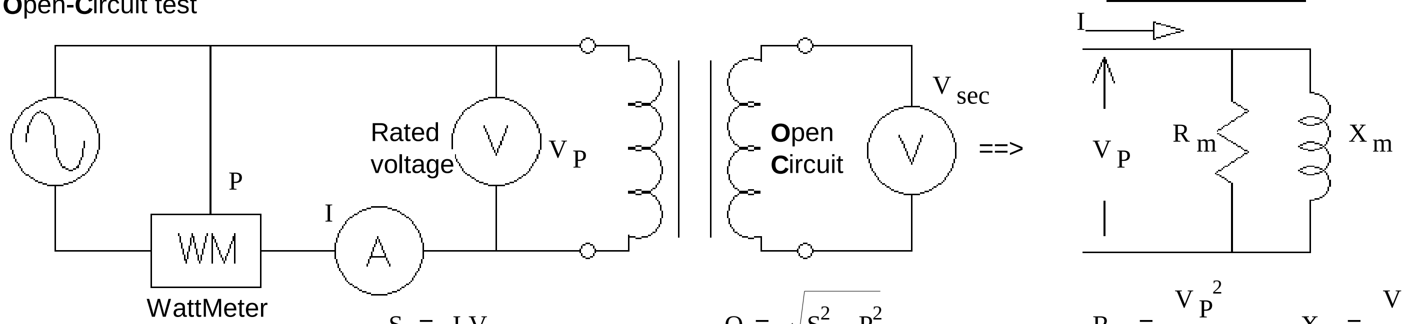
Voltage regulation $\%VR = \frac{V_{no\_load} - V_{full\_load}}{V_{full\_load}}\cdot 100\cdot\%$

Note: A low $\%VR$ is good and a high $\%VR$ is bad, counter-intuitive.

Efficiency $\eta = \frac{P_{out}}{P_{in}}\cdot 100\cdot\%$

**O**pen-**C**ircuit test

Model reduces to




$S = I \cdot V_P$ $\quad Q = \sqrt{S^2 - P^2}$ $\quad R_m = \dfrac{V_P^{\,2}}{P}$ $\quad X_m = \dfrac{V_P^{\,2}}{Q}$

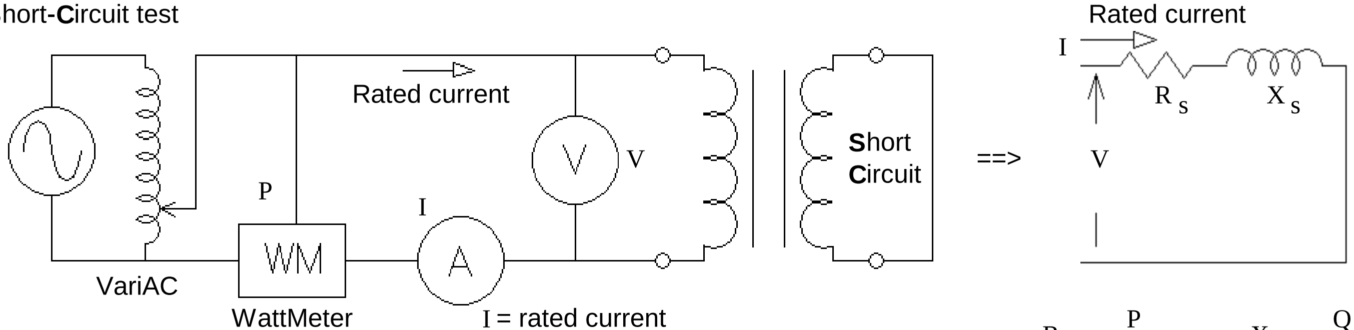
$V_P$ = rated voltage

$I$ = "Magnitization current"

Turns ratio to use in the model: $\dfrac{N_1}{N_2} = \dfrac{V_P}{V_{sec}}$

**S**hort-**C**ircuit test

Rated current




$I$ = rated current

$S = I \cdot V$ $\quad Q = \sqrt{S^2 - P^2}$ $\quad R_s = \dfrac{P}{I^2}$ $\quad X_s = \dfrac{Q}{I^2}$

Determining $\dfrac{N_1}{N_2}$ if you're working from transformer ratings and parameters.

Manufacturers of transformers are well aware of $R_s$ and $X_s$ and how they reduce the output voltage, so they add a few windings (1 - 5%) to the secondary in order to make up for the loss. This lowers the effective turns ratio of the ideal transformer in the model by the same 1 - 5%.

If you're given transformer ratings as $V_{Prated}/V_{Srated}$, & $S_{rated}$ along with $R_s$ and $X_s$ , what turns ratio ( $N$ ) would the manufacturer actually use for the transformer?

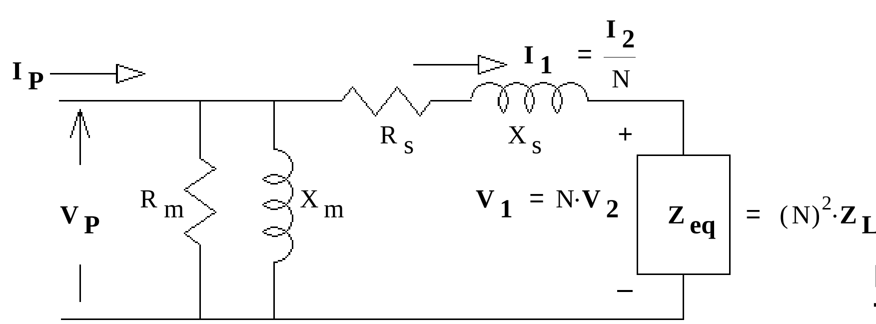
The following calculations are based on: $V_P = V_{Prated}$ $\quad V_S = V_{Srated}$ $\quad P_{out} = S_{rated}$ and $pf = 1$

Then: $R_L = \dfrac{V_{Srated}^{\;2}}{S_{rated}}$ define: $R_x = \dfrac{V_{Prated}^{\;2}}{S_{rated}} - 2 \cdot R_s$ for ease of calculation below

$R_L$ , referred to primary side = $R_{eq} = \dfrac{R_x + \sqrt{R_x^{\,2} - 4 \cdot \left(R_s^{\,2} + X_s^{\,2}\right)}}{2}$ and, $N = \sqrt{\dfrac{R_{eq}}{R_L}}$

Finding $R_{eq}$ required lots of messy algebra, which I'm skipping here.
Just use the calculations above as formulas if you're not given a value for $N$ along with the other parameters.

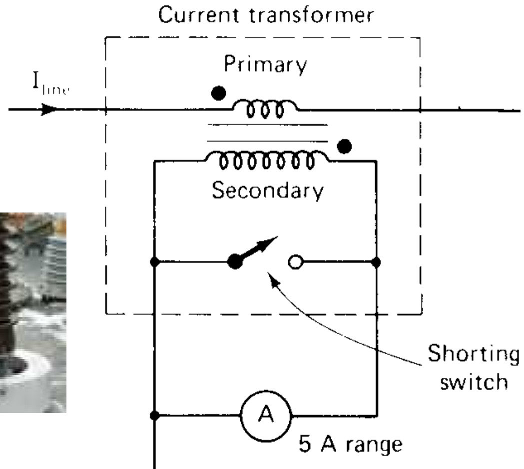
The model becomes:



## Special Sensing Transformers

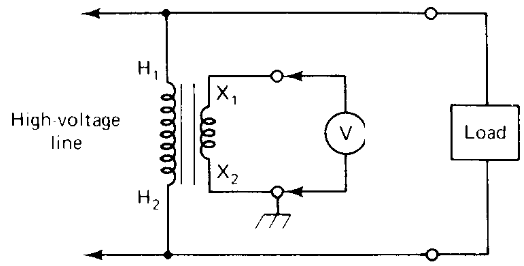
(IET Wiley)

CT




(Ryff, Fig.7.16)

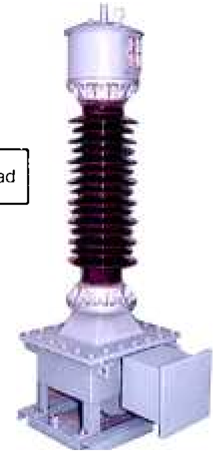
The secondary **must** always be shorted or nearly shorted!




(Ryff, Fig.7.17)

"Potential" transformer, for voltage monitoring

VT or PT



base grounded

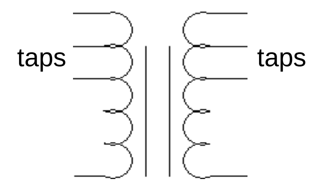
(powerlinedelhi)

Many newer PTs are actually voltage dividers, not transformers.

## Other Transformers

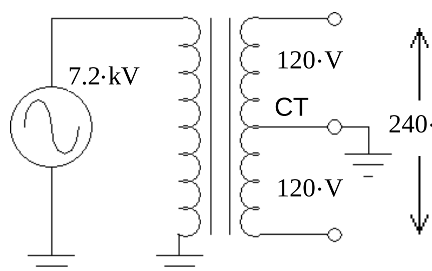
Multi-tap transformers

Many transformers have more than two connections to primary and/or the secondary. The extra connections are called "taps" and may allow you to select from several different voltages or get more than one voltage at the same time.

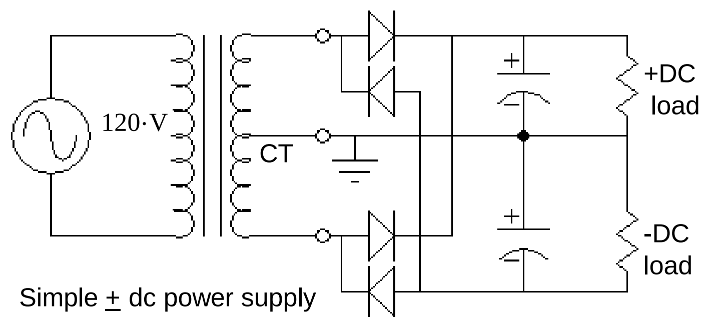



A center tap is very common.

(Wikipedia)

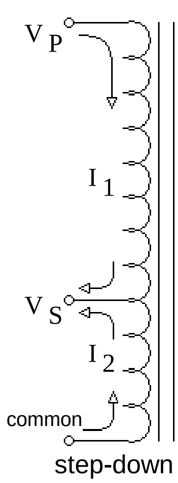



Typical tranformer for residential distribution




Simple $\pm$ dc power supply

Autotransformers




Single-winding transformers where the primary and secondary share windings. For step-down, the secondary is some fraction of the primary. For step-up, the primary is some fraction of the secondary.

Because of the way the currents flow within the windings, the current in or out of the low-voltage side is greater than any current within the windings. Less current means that autotransformers can be economical.

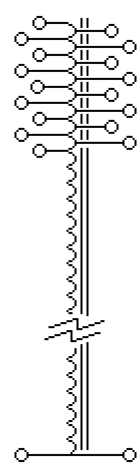
A variAC is an adjustable autotransformer.

Normal transformers can also be wired as autotransformers. More info to come.

Load tap changing

Multiple taps near the top of the transformer can be used to boost or buck (reduce) the voltage a bit. Transformers like this are often used in substations for voltage regulation. Typically, they can adjust the voltage $\pm$ 10% in 33 steps (0.625% per step). Those that can change taps while under load are called "Load tap changing". They can either be regular transformers or autotransformers, the latter are usually just called "voltage regulators". Most can be set up to work automatically.

The tap changing circuitry is not shown at right. It can be rather tricky in that it can not short two taps together nor can it open the circuit during switching.



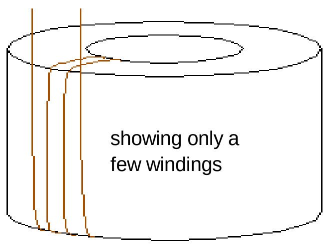
Voltage Regulator

Isolation Transformers

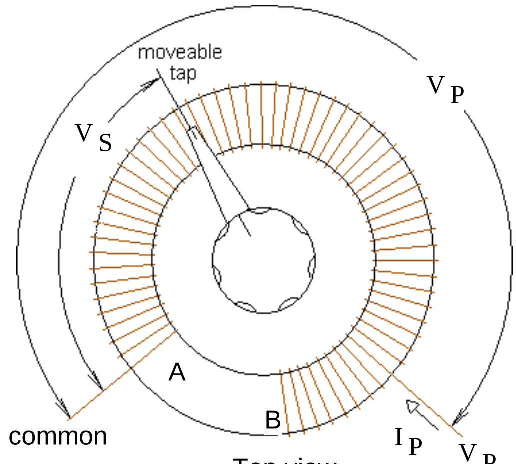
All transformers (except autotransformers) isolate the primary from the secondary. An Isolation transformer has a 1:1 turns ratio and is just for isolation.

## VariAC-type Autotransformer

This adjustable autotransformer is wound on a toroidal core.



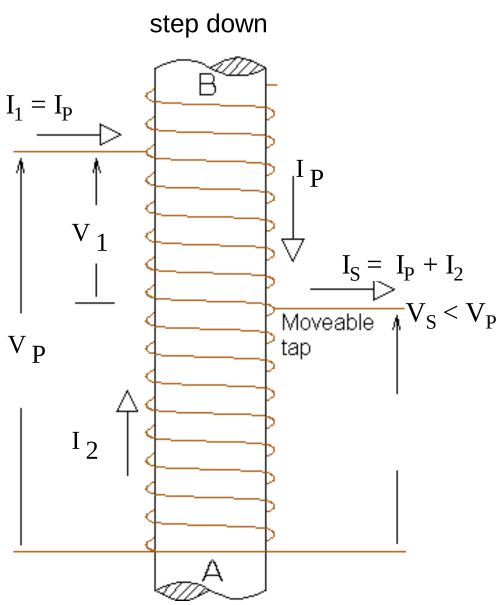

Side view



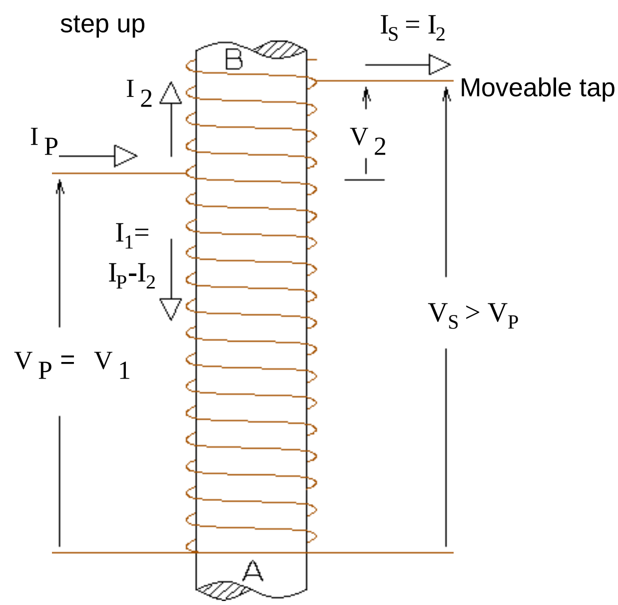

Top view

(Staco Energy)

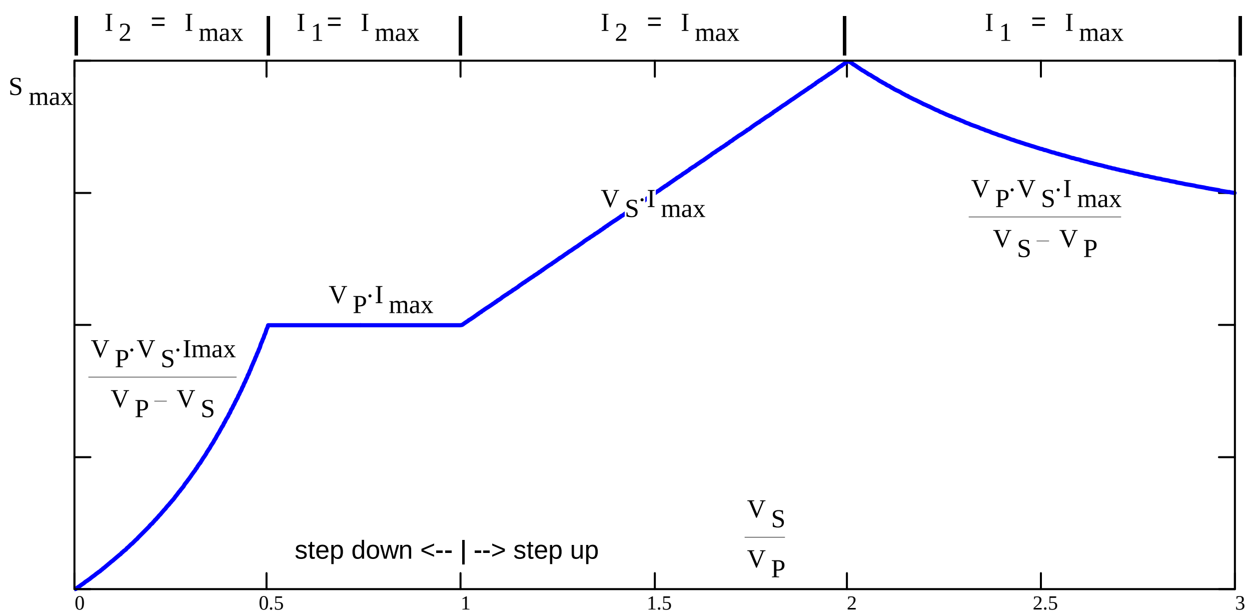
If you cut the toroid open and straightened it out, you would get the views below.



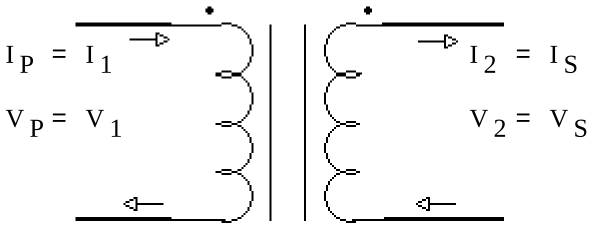

OR




Vari-AC type autotransformer "Rating" , Based or the maximum winding current: $I_{max}$



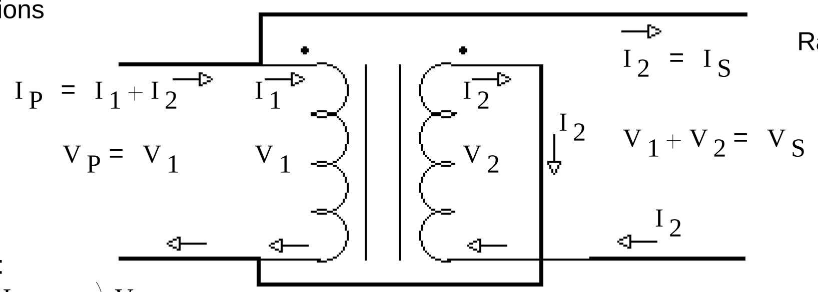
Regular winding connections




## Auto Transformer Connections

4 basic possibilities Note: Sources and Loads are not shown below.

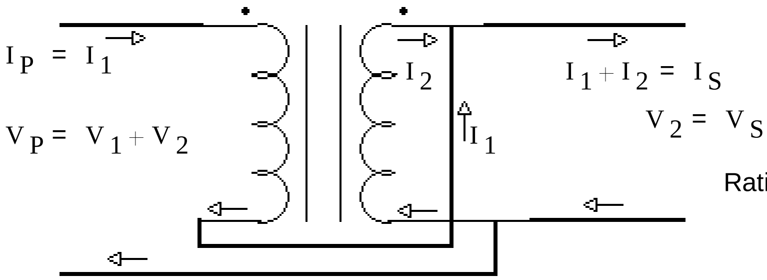
Addition connections




Rating: $I_{2\_rated} \cdot V_S$

Or:

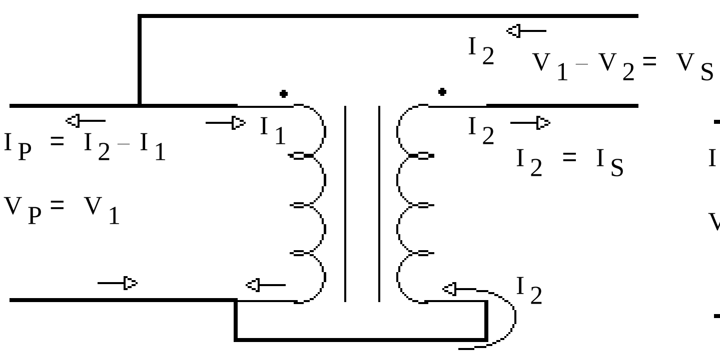
OR, Rating:
$(I_{1\_rated} + I_{2\_rated}) \cdot V_P$

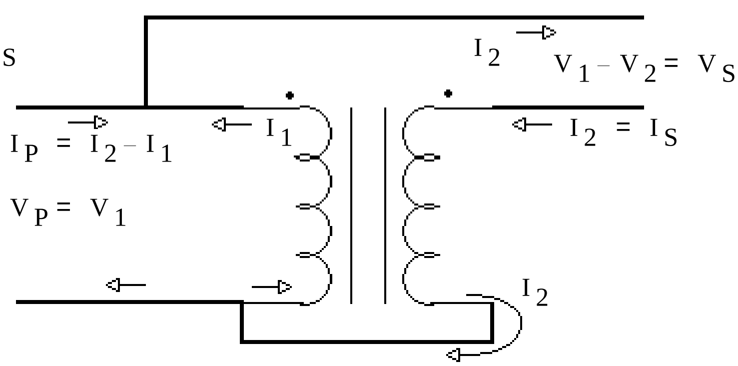



Rating: $(I_{1\_rated} + I_{2\_rated}) \cdot V_S$
OR: $I_{1\_rated} \cdot V_P$

Subtraction connections

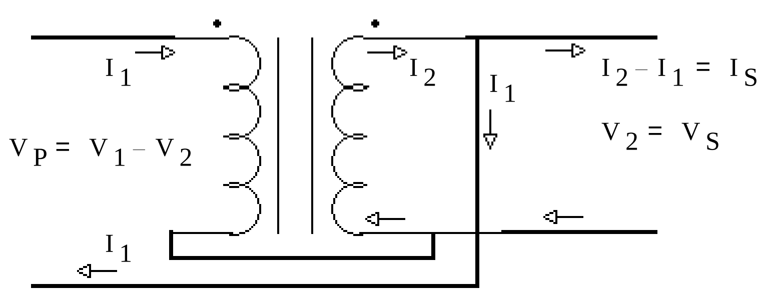
Currents $I_1$ and $I_2$ are flowing reverse of normal.




Rating: $(I_{2\_rated} - I_{1\_rated}) \cdot V_P$ OR: $I_{2\_rated} \cdot V_s$

Power Flow Through Transformer



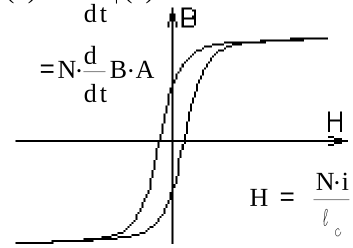

Rating: $(I_{2\_rated} - I_{1\_rated}) \cdot V_S$ OR: $I_{1\_rated} \cdot V_P$

Primary and Secondary could be swapped on any of these connections for an additional 4 possibilities

## Inrush current

When a transformer is de-energized (switched off) its core may remain partially magnetized. When it is then re-energized (switched on) it may take several cycles before the B and the H re-center around the 0,0 point of the B-H plot. That can result in pushing the core far into saturation with large peaks of magnetic field intensity (H). H is directly proportional to current, so there are correspondingly large peaks of current. This inrush current is not sinusoidal and usually has a large DC component. Since it is dependent on where in the voltage cycle the transformer was de-energized it will be different each time the transformer is re-energized.

$$v(t) = N\cdot\frac{d}{dt}\phi(t) = N\cdot\frac{d}{dt}B\cdot A$$




$$H = \frac{N\cdot i}{\ell_c}$$

Note: The "A", above is core cross-sectional area, NOT Amps

Normal inrush currents can be just as large as abnormal short-circuit currents, yet protection devices (breakers and fuses) should not trip or blow-- a difficult protection problem.

Any device with a magnetic core will experience similar inrush currents.

## Cooling and Oil-Immersion

High-voltage transformers are almost universally immersed in oil. That is, the core and windings are in a big enclosure filled with oil. Oil is a much better electrical insulator than air and also has much better thermal conductivity. Typically, it's mineral oil, but other, more expensive, oils and chemicals are also used to reduce fire and/or environmental hazards. PCBs are no longer used. Although PCBs reduced the fire risk, they're highly toxic and stay in the environment a long time.

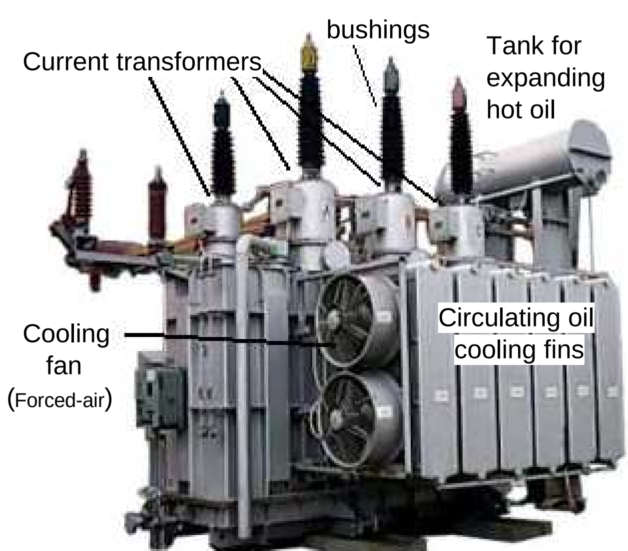
Core losses in a transformer will cause it to heat up even if it's not loaded. $I^2R$ losses increase the heating under loaded conditions. Small transformers may just be air-cooled, but larger transformers require more cooling. Large oil-filled transformers typically cool the oil in radiators with fins next to the transformer. Those fins often have fans for forced-air cooling and the oil may be pumped through the transformer for forced-oil cooling. Transformers often have a tank to accommodate the thermal expansion of the oil. A bladder or inert gas inside the tank prevents contact with air.

| | | |
|---|---|---|
| Cooling Types: | AA | Dry-type, Air cooled |
| | AFA | Dry-type, Forced-Air cooled |
| | OA | Oil Immersed, Air-cooled |
| | OA/FA | Oil Immersed, Air / Forced-Air cooled |
| | OA/FA/FOA | Oil Immersed, Air / Forced-Air / Forced-Oil and air cooled |

### Dissolved Gas Analysis

Analysis of the dissolved gasses in the oil can reveal information about the health of the transformer. The simple version: Oxygen and Nitrogen indicate the oil has had contact with air. Carbon monoxide and dioxide indicate insulation degradation. Hydrogen indicates corona discharge. Methane, ethane, ethylene, and acetylene all indicate increasing levels of electrical faults and/or overheating with acetylene being the worst, indicating arcing. The oil is also checked for water, even a little of which is very bad. Regular maintenance includes filtering and drying the oil.

Large 3-phase Substation Transformer

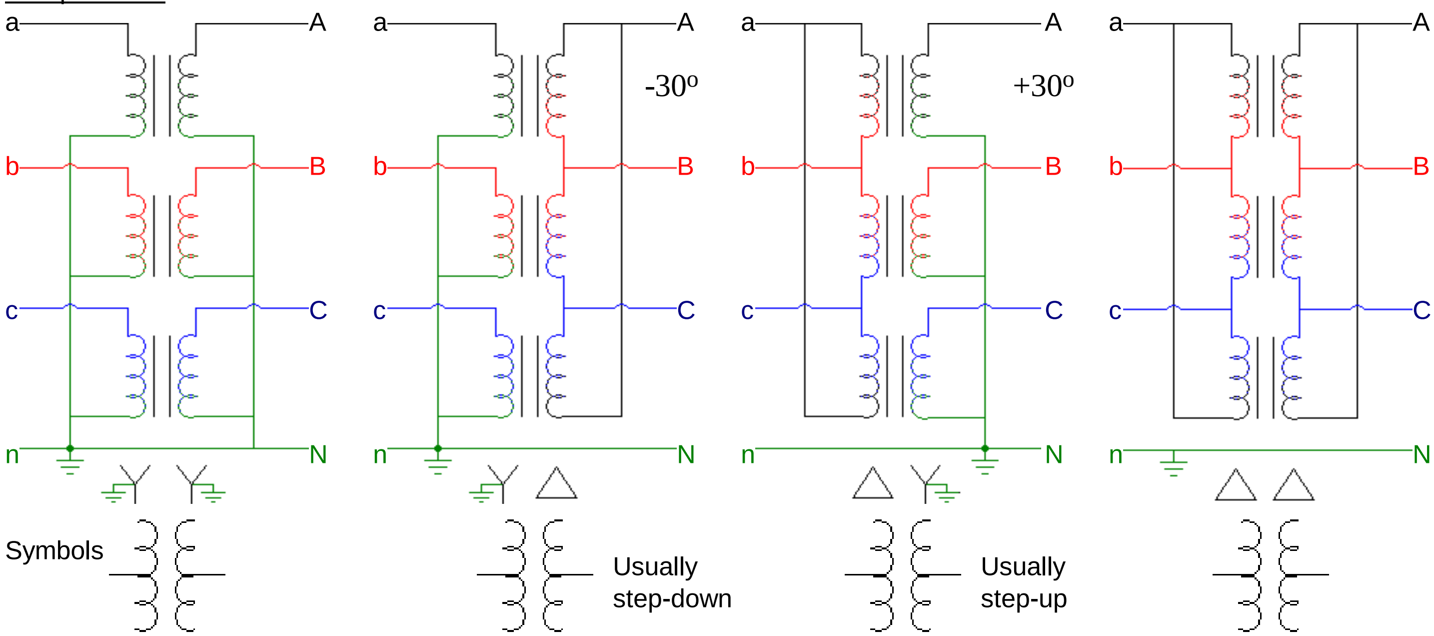



(Exporters India)

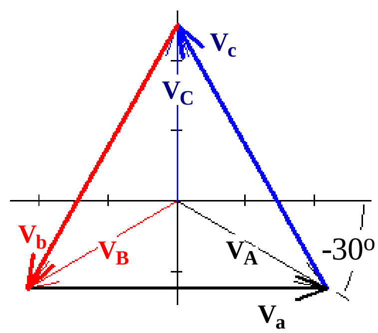
Mineral Oil is Flammable (or is that inflammable?)

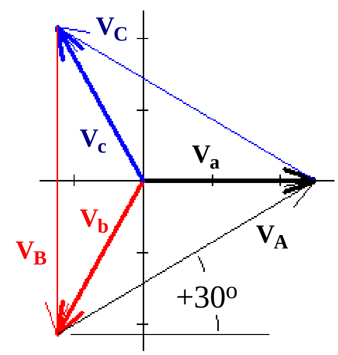
(cbn.co.za)

Multiple cores




Y-Y transformers usually have a tertiary winding for the 3rd harmonic current, see below.

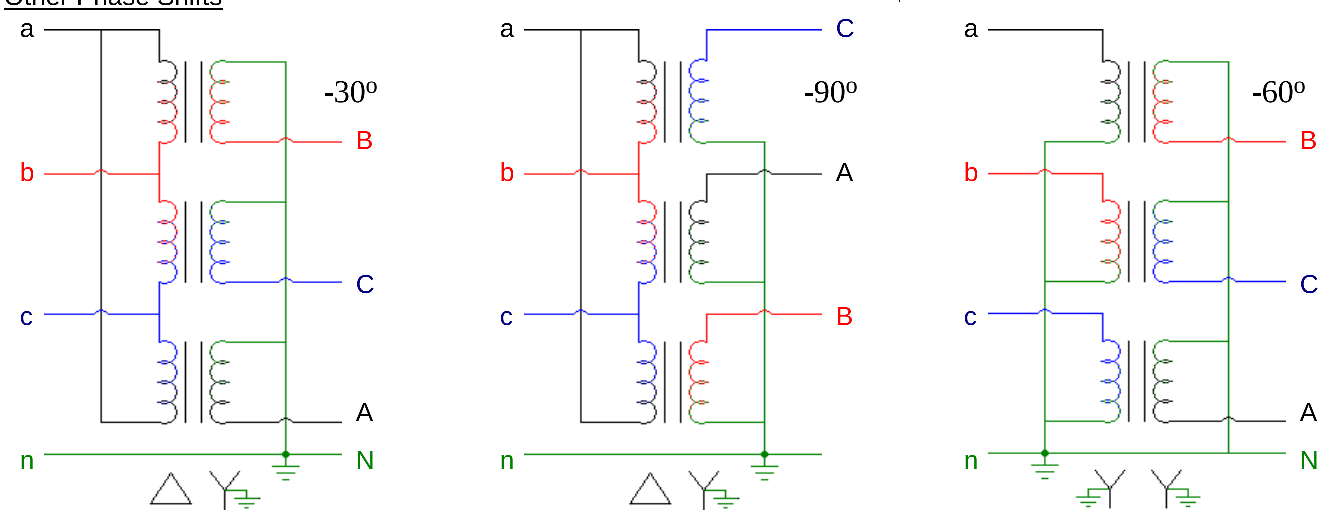


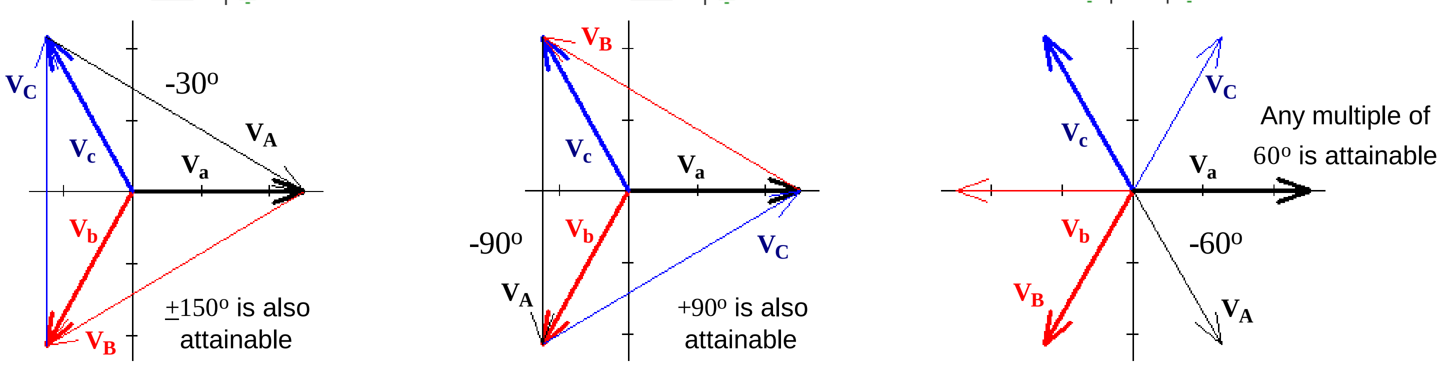




The Δ-Δ configuration can get by with just 2 transformers, at 58% VA.

**Thick lines are the inputs**
Thin lines are the outputs

Other Phase Shifts

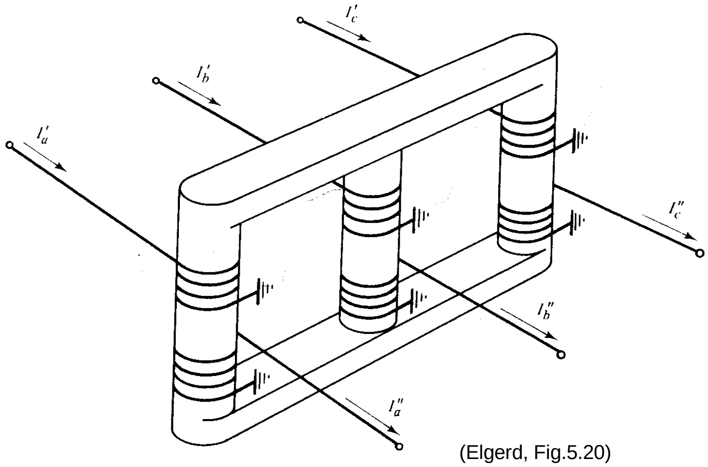


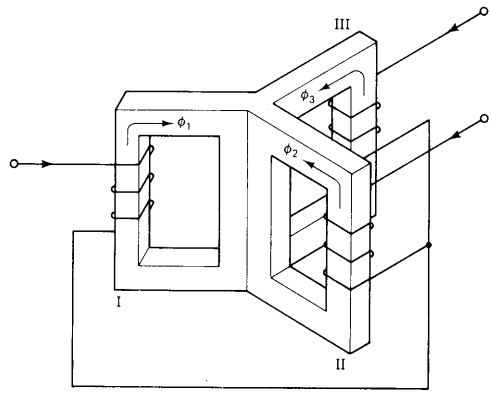

These can also be wired Y- Δ

## Single-Core 3-phase Transformers

Cheaper and have less core loss than using individual cores or transformers.




(Elgerd, Fig.5.20)



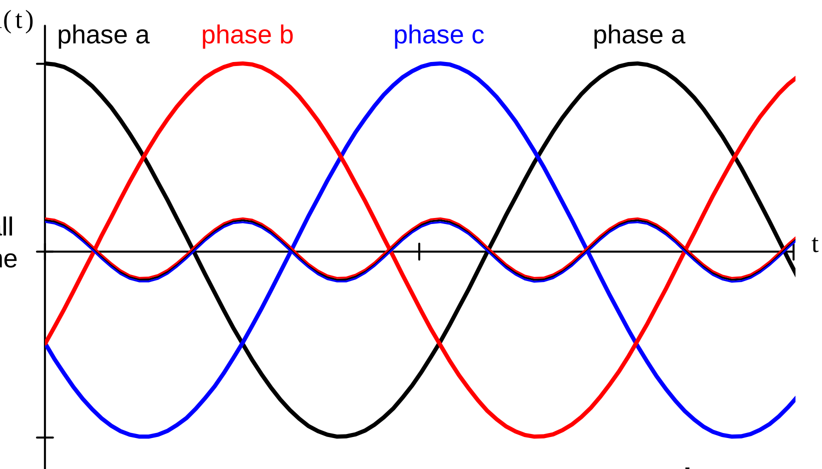

(Ryff, Fig.7.18)

Single-core transformers can also create all phase shifts shown on the previous page.

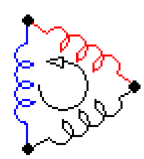
## Third-Harmonic Currents

Third-harmonic currents (due to B-H non-linearity) add up to a significant neutral current.

The 3rd harmonic of all 3 phases are the same




Any $\Delta$-connected winding will allow the third-harmonic current to flow in a loop.

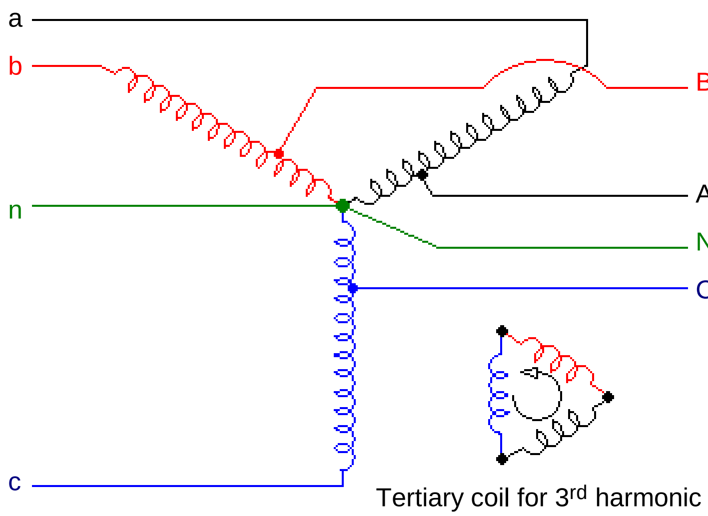


(iStock)

(ITG LLC)

## 3-phase autotransformers

Becoming more popular because they're cheaper for a given VA.

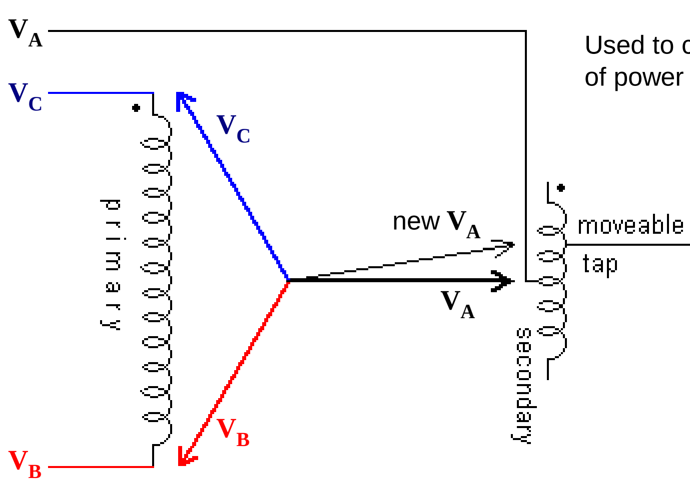



Tertiary coil for 3[rd] harmonic current. Sometimes this is used for "station power", that is, used to power the substation.

(Arn)

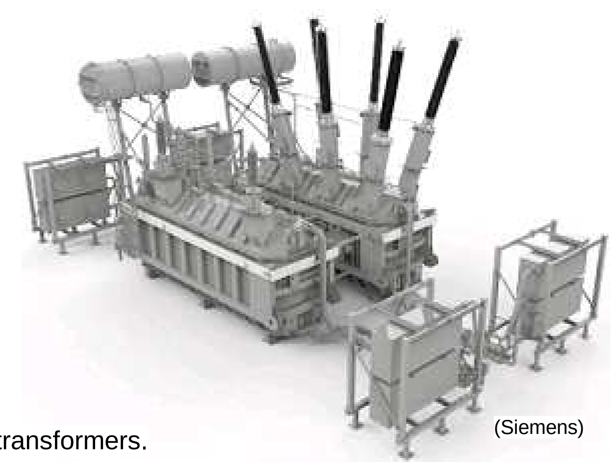
345kV/138kV Autotransformer at Terminal Substation in Salt Lake City. Note oil tank and cooling fins.

## Phase-Shifting Transformers




Used to control the direction of power flow on the network

new $V_A$ phase shifted

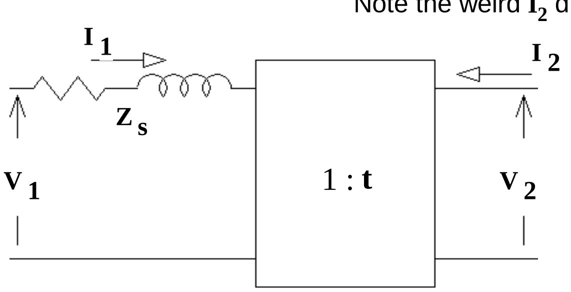


(Siemens)

Phases B and C are shifted in exactly the same way, with two other transformers.

### Off-Nominal Turns Ratio

Note the weird $I_2$ direction




If there is a phase shift, $\mathbf{t}$ will be complex

$$Z_s = \frac{1}{Y_s}$$

$$\begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{bmatrix} Y_s & -\frac{Y_s}{t} \\ -\frac{Y_s}{\bar{t}} & \frac{Y_s}{(|t|)^2} \end{bmatrix} \cdot \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$$

$\bar{t}$ = complex conjugate of $\mathbf{t}$