PEEE - 18.

Date 16. 10. 21

Semiconductor & PN Junction

Materials can be classified according to their electrical properties:

1. Conductors
2. Insulator
3. Semiconductor.

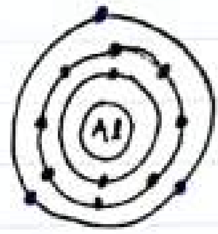
TL;DR → > ~~4~~ 4 valance. → Insulators

→ = 4 valance → semiconductors.

→ < 4 valance → Conductors.

1. Conductors.

- Atoms can have 1, 2, or 3 very loosely bound valance electrons
- Valance electrons are electrons at the outermost orbit of the atom. Such electrons can ~~easily~~ easily break away and become ~~a~~ free electrons.
- Hence a conductor has many free electrons available to support current flow when a voltage is applied.



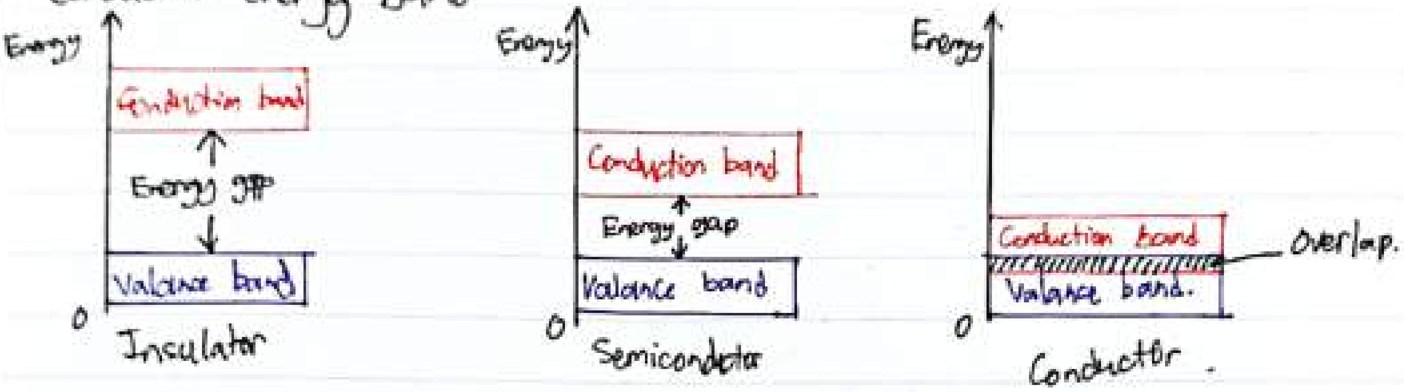
2. Insulator.

- Materials that don't conduct electrical current under normal conditions.
- Usually compounds rather than elements.
- Atoms have 5 or more very tightly bound valance electrons which cannot break away easily from the atoms.
- Hence very few free electrons present to support current flow when voltage is applied

3. Semiconductor.

- Materials which electral conductivity is between that of conductor & insulator.
- Intrinsic (pure) semiconductor is neither a good conductor nor good insulator.
- They have 4 valance electrons which are moderately bound to the atom.
- Examples → carbon, silicon, Germanium

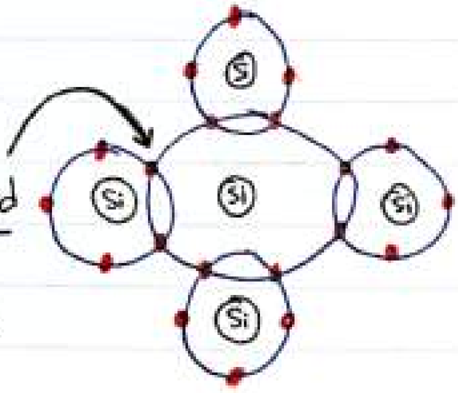
When a valance electon aquires enough additional energy, it is able to leave it's valance shell and become a free electron. Such electrons are said to move from the valance energy ~~band~~ bond to the conduction energy band



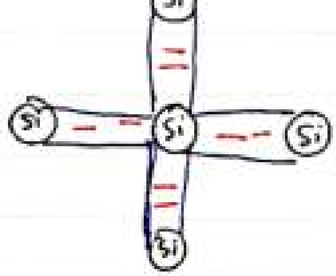
The conduction band and valance band in conductor overlaps resulting in large number of free electrons even without external energy.

Covalent bond.

- Pure (intrinsic) silicon has <u>no impurities</u> and is a <u>crystalline material</u>
- Its atoms are held together by <u>covalent bonds</u> (sharing of electrons)
  - Center atom shares 1 electron with each of four surrounding atoms creating a <u>covalent bond</u> with each.
- The surrounding atoms are in turn bonded to other atoms, and so on.

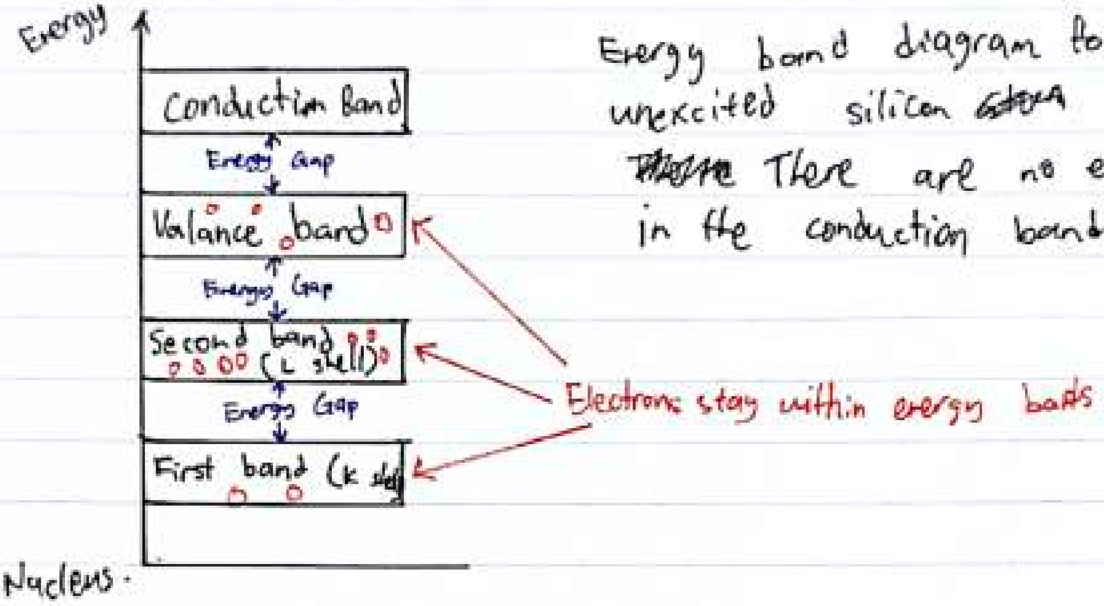


- Another way to represent the covalent bonds.
- Bonding Diagram. The red negative signs represent the shared valance electrons.



Semiconductor & PN Junction

- If an electron is unexcited, it stays ~~within~~ within it's ~~pe~~ prescribed atomic shell.
- Atomic shells can be looked upon as energy bands where electrons with similar energy levels reside.



Energy band diagram for an unexcited silicon ~~atom~~ atom. ~~There~~ There are no electrons in the conduction band.

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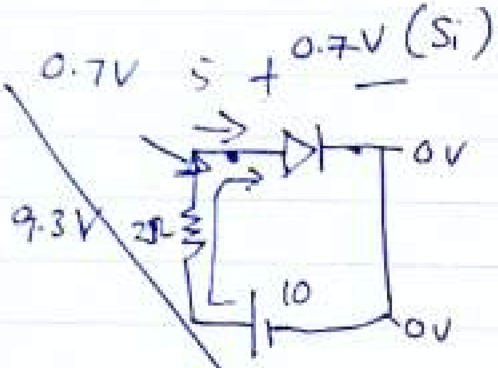
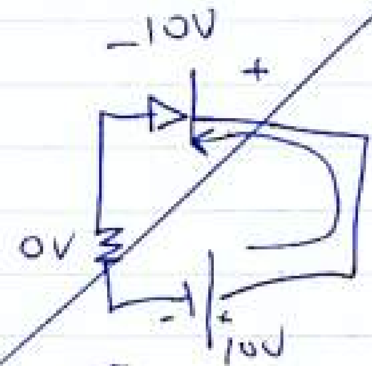


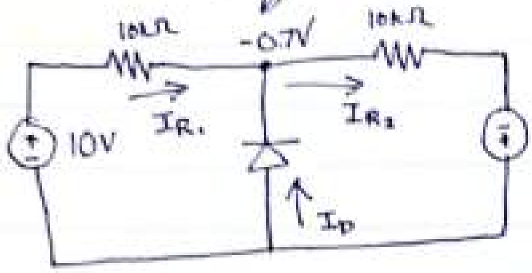


$I = \frac{9.3}{2} = $ ____

$I = 0$.

reverse, open.
doped w trivalent
reduce free electron → add trivalent.

forward biased → voltage must be smaller than -0.7V

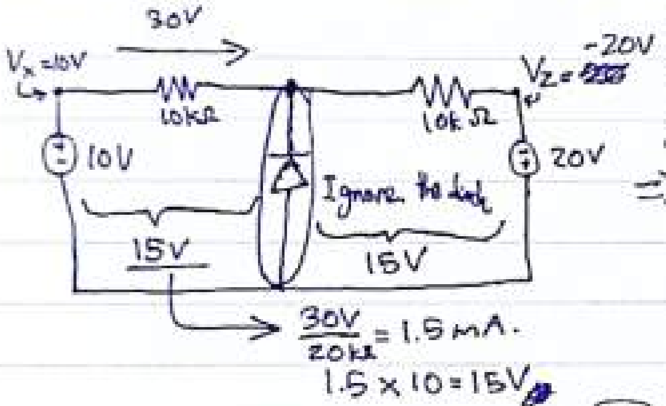


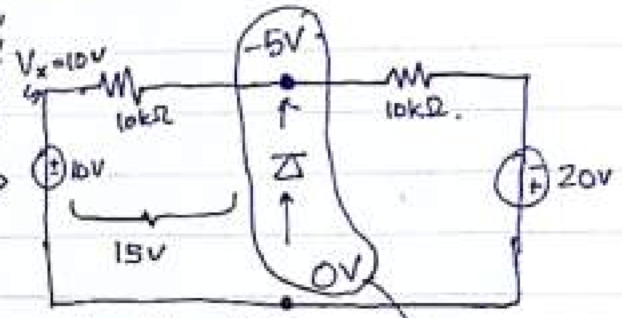
↑
-20 (oposite direction)

$$I_{R_1} + I_D = I_{R_2}$$
$$I_D = I_{R_2} - I_{R_1}$$

$$I_{R_1} = \frac{10V-(-0.7V)}{10k\Omega} = 1.07mA.$$
$$I_{R_2} = \frac{(-0.7V)-(-20V)}{10k\Omega} = 1.93mA$$
$$I_D = 1.93 - 1.07 = 0.86mA$$

How to tell if it is forward / reversed biased.





$10 - 15 = -5V$
voltage drop is 15V

0 can go to -5 means forward.

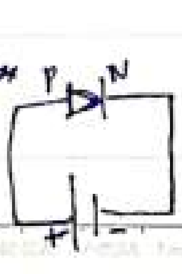
→ reversed biased.

Forward → current can flow
Reversed → current cannot flow.

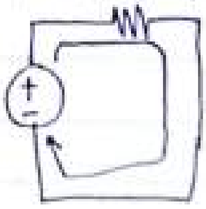
positive to negative
→ reversed.

If B is 10V,
A must be 10.7V or more
∴ must have 0.7V difference.

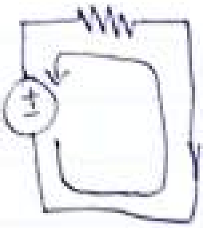
$\boxed{-0.7V}$



positive to positive?
↓
forward.



Conventional current theory → calculation use this positive to negative



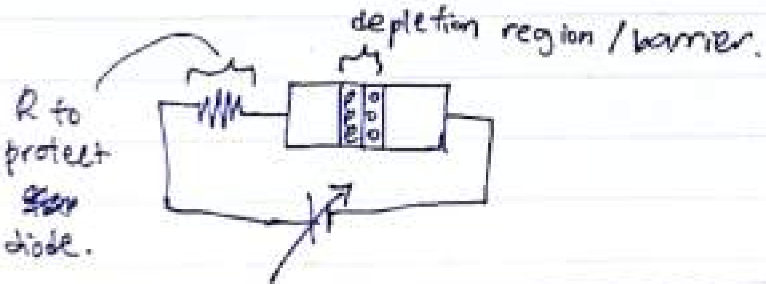
Electron flow → IRL is this cuz current flow is due to electron flow → negative to positive.

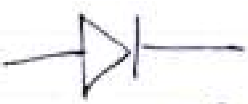
P-N Junction.

When they are met, all the electron from the N-type will move to the P-type.

depletion region

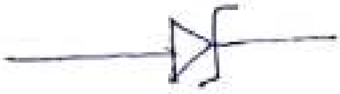
This makes the P-type more negatively charged while the N-type is more positively ~~charged~~ charged.





Normal Diode.

(forward biased)



Zener Diode (reversed biased).

given voltage almost constant if used in reversed biased.

If zener diode in forward biased will act like normal diode.

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Semiconductor & PN Junction.

Materials can be classified according to their electrical properties:

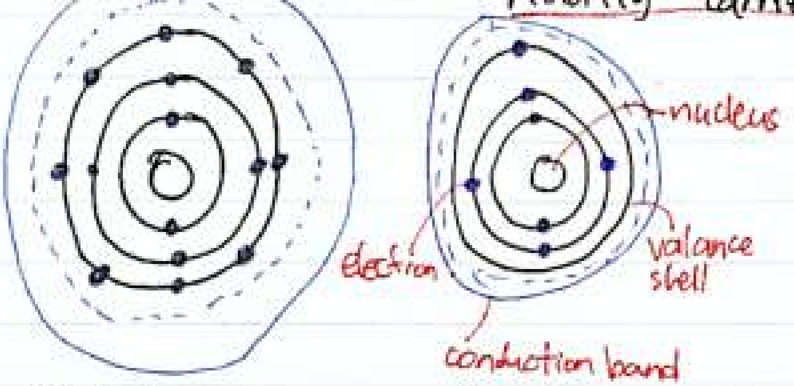
1. Conductor → - Valance shell have either 1, 2, or 3 electrons.
   - Since electron number is very low or close to 0, thus they will happily give out their electrons, hence they are good at conducting current.
2. Insulator → - Valance shell have either 5, 6, 7 or 8 electrons.
   - Since electron number are closer or are 8, thus they will not easily give out electron, hence they are bad at conducting current, as the flow of current is also called as the flow of electron.
3. Semiconductor → - Valance shell have exactly 4 electrons.
   - They are in the middle, so they are not easily giving or taking electrons.
   - It's neutrally charged.
   - Example : Silicon, Germainium.
   - The pure semiconductor are also known as intrinsic (pure) semiconductor.

The 2 types of Semiconductor:

- N-type semiconductor. → Extrinsic (impure) semiconductor.
  - Negative type (charged)
  - Have 1 extra electron
  - Wants a hole.
  - The atom with the extra electron is called an impurity atom, where it has 5 ~~electron~~ electrons, this is called "pentavalent atom"
  - This makes it more negatively charged:
    - Majority carrier are electrons
    - Minority carrier are holes.

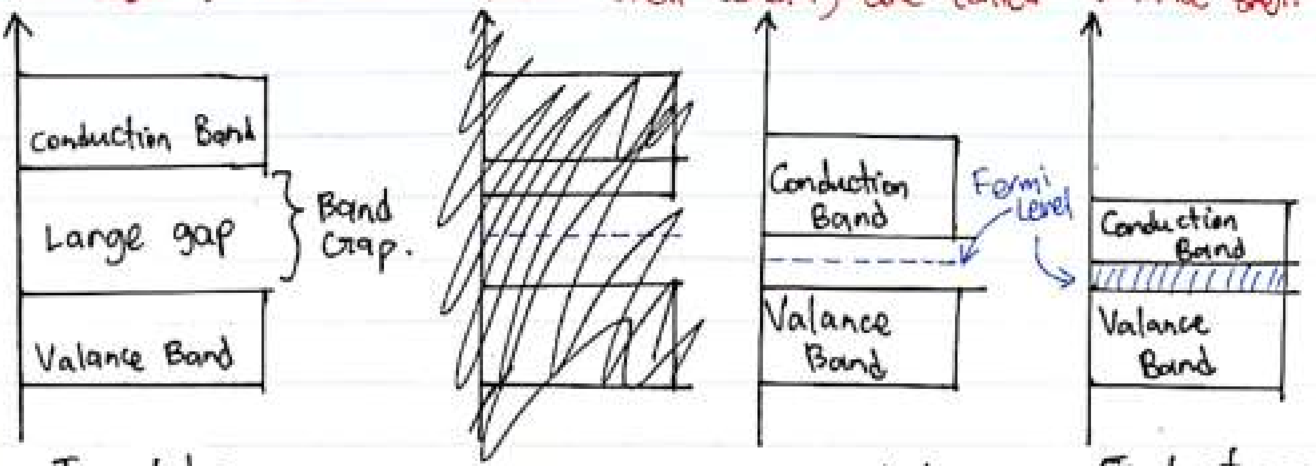
☆ Majority → i.e. there are 2 million N-type semiconductor, this will also mean that there will be 2 million extra electrons, this means that there are more electrons than holes, thus this is called as the majority carrier.

- P-type semiconductor → - Extrinsic (impure) semiconductor.
  - Positive type (charged)
  - Have 1 extra hole / 1 less electron.
  - wants an electron.
  - The atom with 1 lesser electron: is called an impurity atom, where it has 3 electrons, this is called "trivalent atom"
  - This makes it more positively charged:
    - Majority carrier are holes
    - Minority carrier are electrons.



Insulator   Conductor   Semiconductor

Valance shell → The outer most shell (orbit) are called valance shell



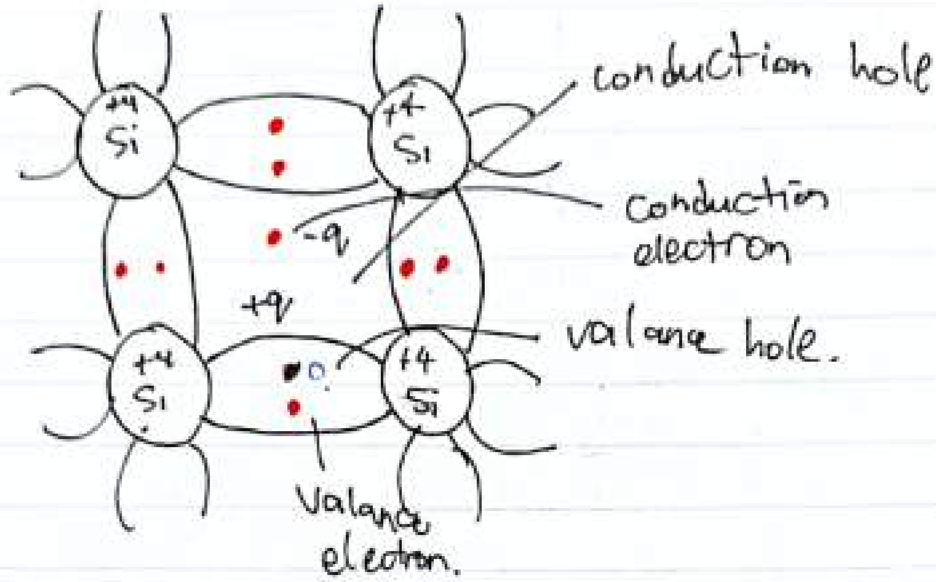
Insulator - Large gap

Semiconductor - Small gap

Conductor - Very close (overlap).

Semiconductor & PN Junction.

Electron - Hole - Pair



- When pure silicon recieves heat or light energy from surroundings, some valance electron will gain sufficient energy to jump from the valance shell into the conduction band.
- Electron - hole - pair refers to the break - away free electrons and the hole left behind. The process is called ionisation.
- The hole is known as a plus (positive charge), as it is positive charged, it is waiting for an electron (which is negatively charged)

electron + hole = electron - hole - pair.

→ Direction of the electron moving.

← Direction of the hole moving.

- The hole is filled with the electron, and place of the original electron (that is now in the new hole) is turned into a hole, the process will happen repeatedly.
- The pure semiconductor consist of N - type and P - type semiconductor.

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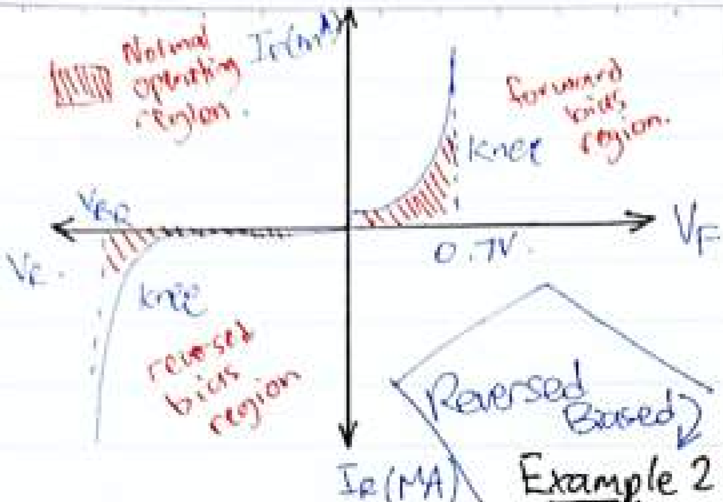
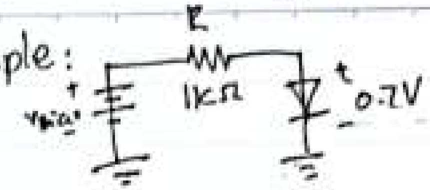


Forward Biased

Example:



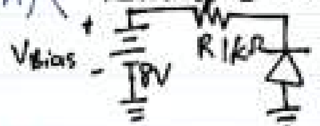
Find I_F and V_R.

$$I_F = \frac{V_{Bias} - V_F}{R} = \frac{8 - 0.7}{1} = 7.3\text{ mA}$$

$$V_R = I_F \times R = 7.3\text{mA} \times 1\text{k}\Omega = 7.3\text{V}$$

Reversed Biased

Example 2:

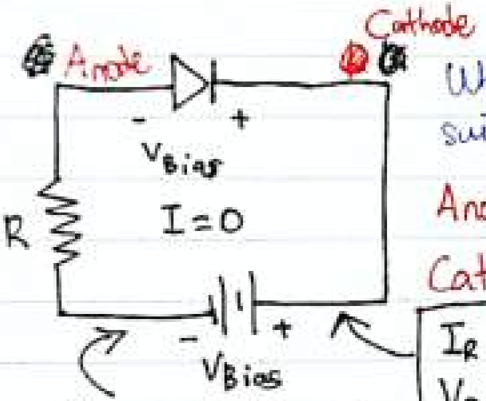


Find I_R, ~~V_R~~ V_R, and V_{Diode}.

$I_R = 0A$, $V_R = I_R \times R = 0A$

$V_{Diode} = V_{Bias} - V_R = V_{Bias} = 8V$

Diode Calculation.



Reversed Biased

When diode is reversed biased, it acts as an open switch.

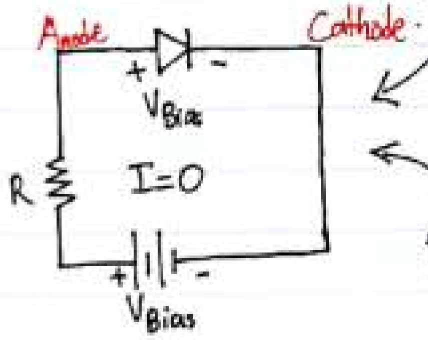
Anode terminal of the diode, connecting to p-region

Cathode terminal of the diode, connecting to n-region

$I_R = 0A$

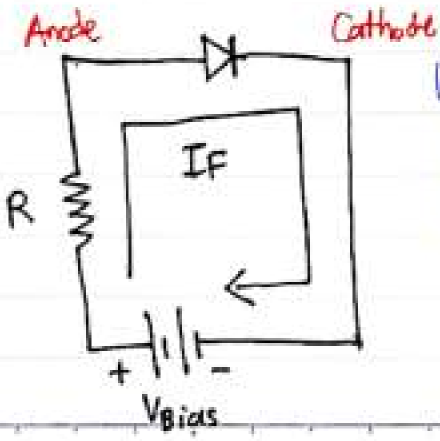
$V_R = I_R \times R = 0V$

$V_{Diode} = V_{Bias} - V_R = V_{Bias}$



When $V_{Bias} < 0.7V$, the diode acts as an open switch.

Forward Biased, but $V_{Bias} < 0.7V$

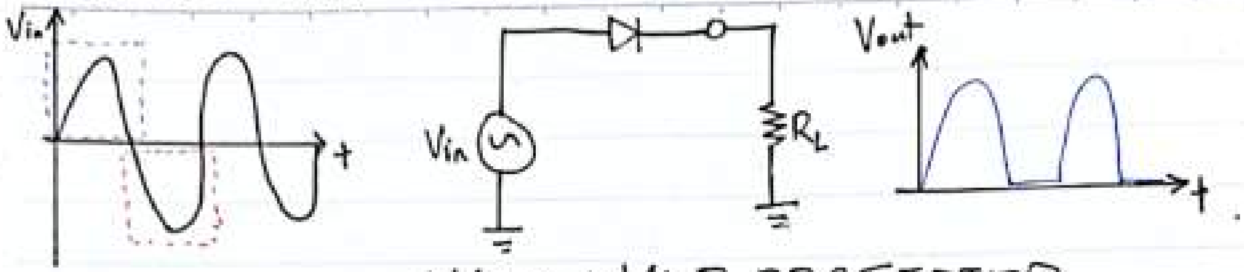


When $V_{Bias} \geq 0.7V$, the diode acts as an closed switch in series with a small voltage supply of 0.7V

$$V_{Bias} = I_F \times R + V_F$$

$$\therefore I_F = \frac{V_{Bias} - V_F}{R}$$

~~Rectifier~~. HALF-WAVE RECTIFIER.

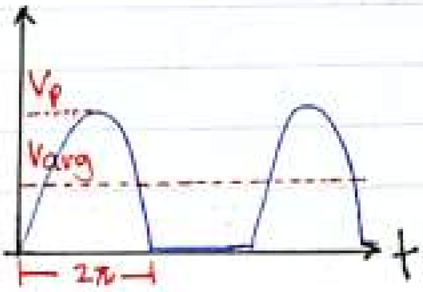


HALF-WAVE RECTIFIER.

- The diode will convert input voltage (Vin) waveform into half wave output (Vout)
  - Only the positive half-cycles appear across the load.
  - ~~Out put~~ Output is a pulsating d.c. voltage.

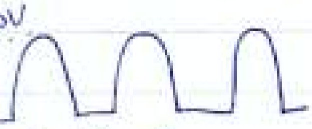
When the input (Vin) goes positive, the diode is forward-biased and conducts current through the load resistor R_L. Thus, this will develop an output voltage Vout across it which has the same shape as the positive half-cycle of the input voltage.

When the input goes negative during the second half of this cycle, the diode is reverse-biased. Thus, ~~the~~ no current flows into the load R_L (i.e. I=0A), so the voltage difference across the load R_L is 0V. $\rightarrow V_{RL} = I_{RL} \times R_L = 0 \times R_L = 0V$



$$\boxed{V_{avg} = \frac{V_p}{\pi}}$$

eg. 100V

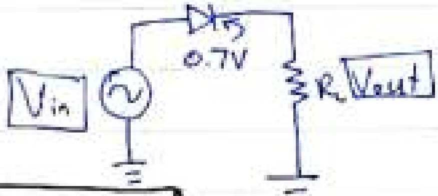


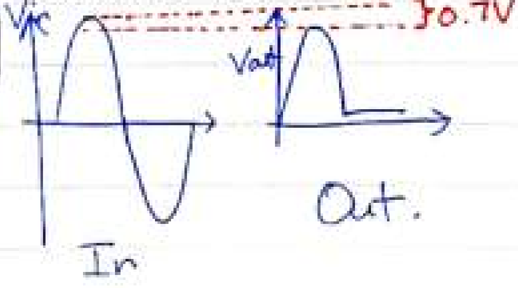
Find Vavg?

$V_{avg} = \frac{V_p}{\pi} = \frac{100}{\pi} = 31.83V$

During the positive half cycle, the input voltage must overcome the barrier potential before the diode conducts current.

Thus, $\boxed{V_{out(p)} = V_{in(p)} - 0.7V}$





$$\boxed{V_{out(p)} = V_{sec(p)} - 0.7V}$$

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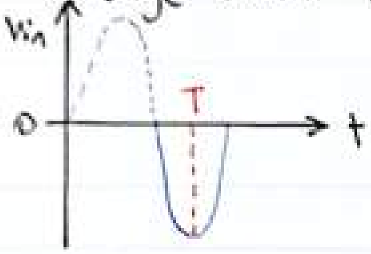
Peak Inverse Voltage (PIV).

- PIV occurs at peak of each negative alteration of the input voltage when the diode is reverse-biased



$$\boxed{PIV = V_{in(p)}}$$

$$\downarrow$$

$$\boxed{PIV = V_{sec(p)}}$$

During the negative half cycle:

$I = 0$

$V_{R_L} = IR_L = 0$

$V_K = V_{GND} = 0$

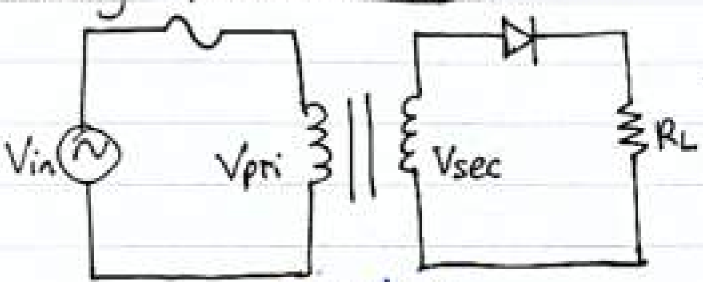
$PIV = V_{KA(max)}$

$= V_{KA} - V_{A(min)}$

$= 0 - (-V_{in(p)})$

$= V_{in(p)}$

Using Transformers



Npri : Nsec

Transformer.

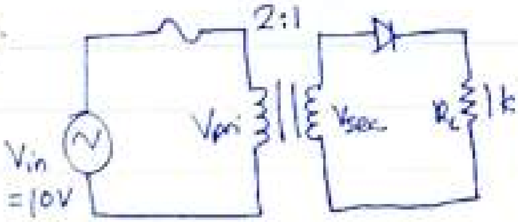
A transformer is often used to couple the a.c. input voltage from the source to the rectifier.

This has advantages:

1) It allows the source voltage to be stepped up or down as needed.

2). The a.c. source is electrically isolated from the rectifier for preventing a shock hazard in the secondary.

e.g.



Find $V_{out(p)}$ when $V_{in} = 10V_{peak}$.

$$V_{sec(p)} = \left(\frac{N_{sec}}{N_{pri}}\right) \times V_{pri(p)} = \frac{1}{2} \times 10V = 5V$$

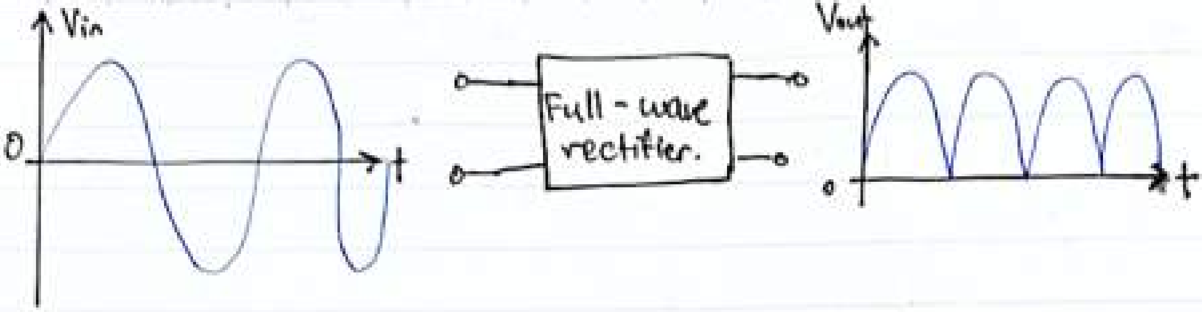
$$V_{out(p)} = V_{sec(p)} - 0.7V = 5 - 0.7V = 4.3V$$

#3

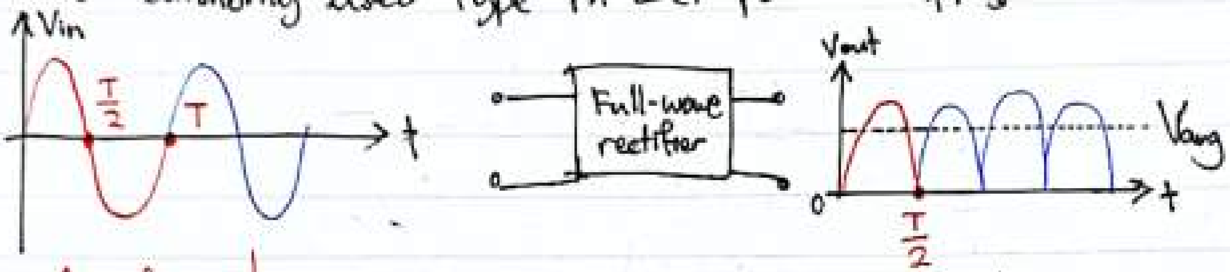
No. PEEE-19

Date 25. 11. 21

Full-Wave Rectifier.



Most commonly used type in d.c. power ~~supplyy~~ supplies.



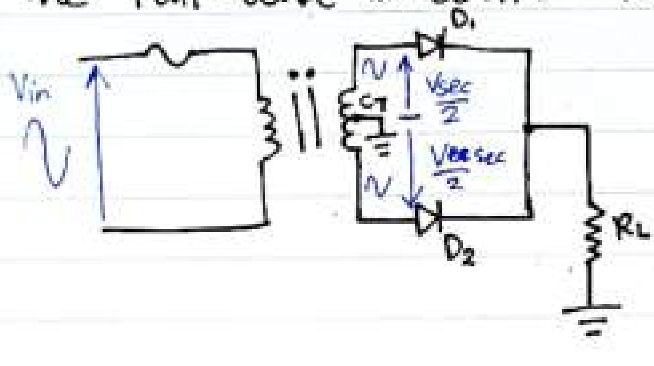
~~fo~~ $f_{in} = \frac{1}{T}$

$f_{out} = \frac{1}{T/2} = \frac{2}{T}$

- Output frequency is twice that of input frequency.
- Average value for a full-wave rectifier sinusoidal voltage is twice that of half-wave.

$$\boxed{V_{avg} = \frac{2V_{out(p)}}{\pi}}$$

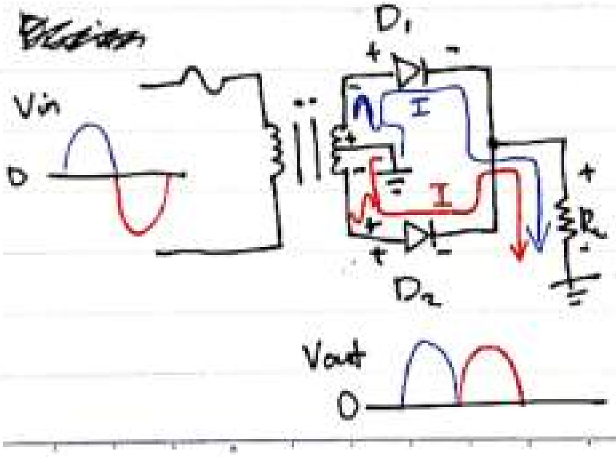
The Full-wave centre-tapped transformer rectifier.



This uses 2 diodes connected to the secondary of a centre-tapped transformer.

$D_1 \rightarrow$ forward biased

$D_2 \rightarrow$ Reversed biased.

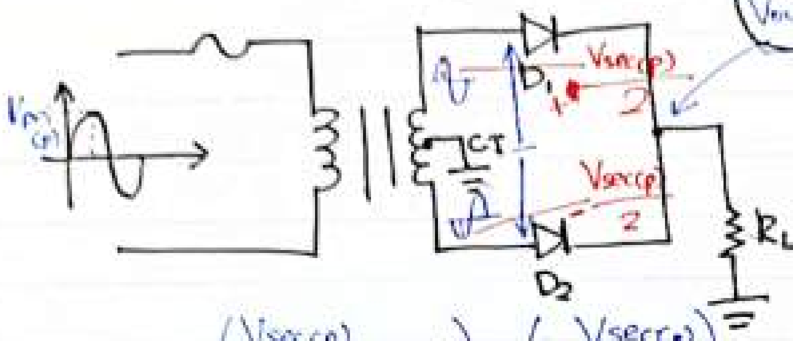


Positive half cycle $\Rightarrow$ current path through D_1 and R_L.

Negative half cycle $\Rightarrow$ current path through D_2 and R_L

Peak Inverse Voltage (PIV)

$$\boxed{V_{out(p)} = \frac{V_{sec(p)}}{2} - 0.7V}$$



When D_2 is reversed biased, the PIV across D_2 is the p.d. between the cathode and ~~anode~~ ~~and~~ anode

$$PIV = \left(\frac{V_{sec(p)}}{2} - 0.7V\right) - \left(-\frac{V_{sec(p)}}{2}\right)$$
$$= V_{sec(p)} - 0.7V$$

As derived previously $\rightarrow$ $V_{out(p)} = \frac{V_{sec(p)}}{2} - 0.7V$

$$\frac{V_{sec(p)}}{2} = V_{out(p)} + 0.7V$$
$$V_{sec(p)} = 2V_{out(p)} + 1.4V.$$

Therefore $\longrightarrow$ $PIV = (2V_{out(p)} + 1.4V) - 0.7V$

$$\boxed{PIV = 2V_{out(p)} + 0.7V}$$

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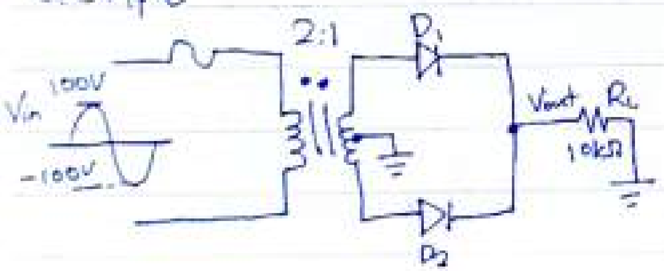
example



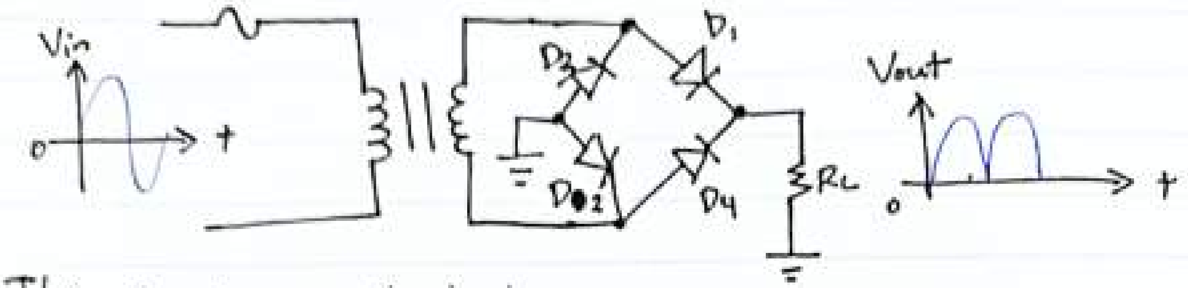
Find a) secondary winding V_p.
b) $V_{out(p)}$
c) PIV

a) $V_{sec(p)} = \left(\frac{N_{sec}}{N_{pri}}\right) \times V_{pri(p)}$
$= \frac{1}{2} \times 100V$
$= 50V$ //

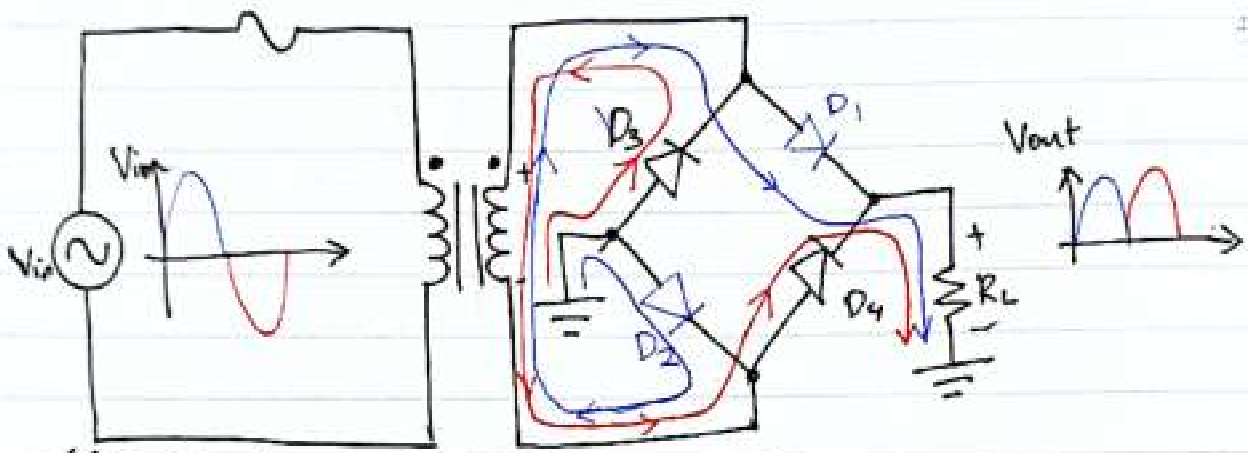
b) $V_{out(p)} = \frac{V_{sec(p)}}{2} - 0.7V$
$= \frac{50}{2} - 0.7$
$= 24.3V$ //

c) $PIV = 2V_{out(p)} + 0.7V$.
$= 2(24.3) + 0.7$
$= 49.3V$ //

FULL-WAVE BRIDGE RECTIFIER



This circuit uses 4 diodes.



~~∴ D_1 and D_2 → forward biased~~
~~D_3 and D_4 → reversed biased~~

Positive half cycle.
- A voltage is developed across R_L in the path shown.
- D_1 and D_2 → forward biased.
- D_3 and D_4 → reversed biased.

Negative half cycle.
- D_3 and D_4 → forward biased.
- D_1 and D_2 → reversed biased.
- Conducts current in the same direction through R_L as during the positive half cycle.

~~Bridge Output Voltage~~

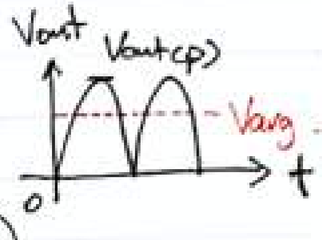
~~Since 2 diode are always in series with the R_L during both half-cycles (positive or negative half cycle). Consider each has a voltage drop of 0.7V each.~~

$$\boxed{V_{out} = V_{sec(p)} - 1.4\,V}$$

Bridge Output Voltage

- Since 2 diodes are always in series with R_L, during both positive and negative half cycles. We can consider each has a voltage drop of 0.7V. Thus,

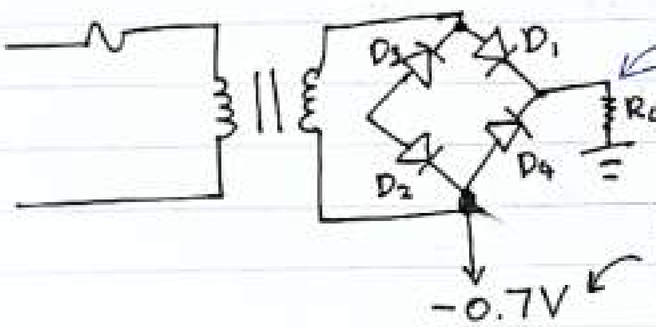
$$\boxed{V_{out(p)} = V_{sec(p)} - 1.4V}$$



- The average output voltage will hence be.

$$\boxed{V_{out(avg)} = \frac{2}{\pi} \times V_{out(p)}}$$

Peak Inverse Voltage (PIV)



$V_{out(p)} = V_{sec(p)} - 1.4V$.

the voltage drop at that point. (from 1 diode)

$$PIV = V_{out(p)} - (-0.7V)$$

$$\boxed{PIV = V_{out(p)} + 0.7V}$$

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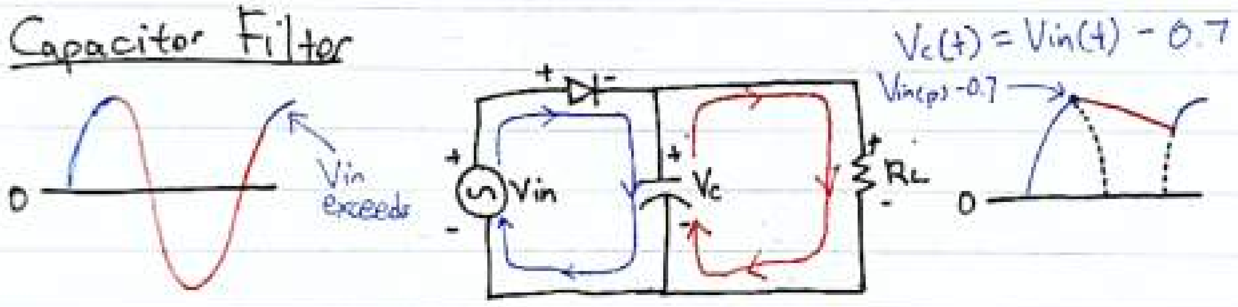
POWER SUPPLY FILTERS

- A Power filter eliminates or reduces fluctuations in output voltage of a rectifier.
- It produces a near constant-level dc voltage.
- Filtering is necessary as electronic circuits need a constant source of dc voltage and current to provide power and biasing for proper operation
- The small amount of fluctuation in the filter output is called ripple.

Capacitor Filter



- During the positive first-quater cycle of the input, the diode is forward biased, allowing the capacitor to charge to within 0.7V of the input peak.
- When the input decreases below its peak, the capacitor retains it's charge and diode becomes reverse-biased because the cathode is more positive than the anode.
- $V_c(t) = (V_{in(p)} - 0.7)\, e^{\frac{-t}{R_L C}}$
- Capacitor discharges only through the R_L at a rate determined by the $R_L C$ time constant (normally long).
- Larger time constant, slower discharge time.
- During the first quarter of the next cycle, the diode will again become forward-biased when the input voltage exceeds the capacitor voltage by approx. 0.7V.

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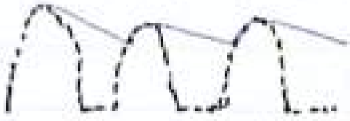
Larger ripple → less effective filtering



smaller ripple → more effective filtering

e.g. ripple factor

$V_{dc} = (8+6)/2 = 7V$

$r = \dfrac{(8-6)}{2\sqrt{3}(7)} = 0.0825V$

Half wave

Full wave

The full wave rectified wave has a smaller ripple for the same R_L and filter Capacitance.

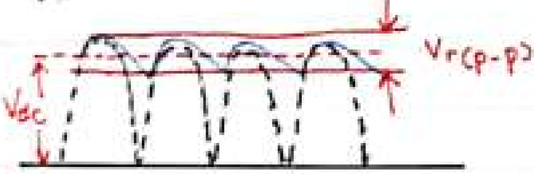
Half-wave

Full-wave.

eg. $f_{hw} = \dfrac{1}{T_{hw}} = \dfrac{1}{20} = 50Hz$

eg. $f_{fw} = \dfrac{1}{T_{fw}} = \dfrac{1}{T_{hw}/2} = \dfrac{1}{20/2} = 100Hz$

Ripple factor



The ripple factor (r) is an indication of the effectiveness of the filter.

$$\boxed{r = \frac{V_{r(rms)}}{V_{dc}}}$$

$V_{r(rms)}$ – rms of the ripple voltage

V_{dc} – dc (avg) value of the filter's output voltage.

$V_{r(rms)}$ can be replaced to $V_{r(p-p)}$

$$\boxed{r = \frac{V_{r(p-p)}}{2\sqrt{3}\,V_{dc}}}$$

$V_{r(p-p)}$ – peak to peak ripple voltage.

☆ The lower the ripple factor is, the better the filter.

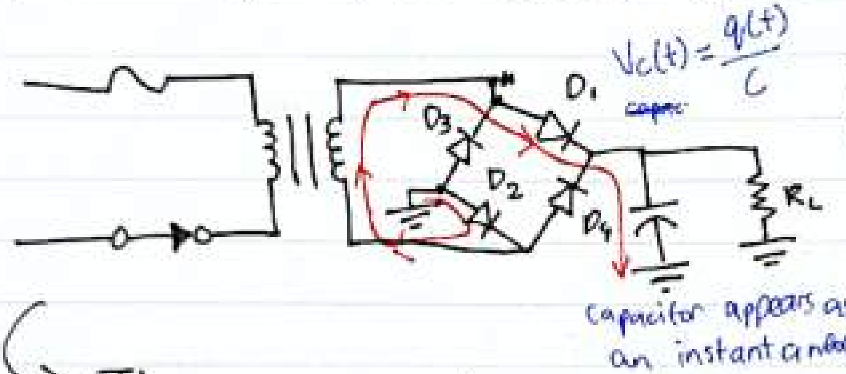
☆ The ripple can be lowered by increasing the value of the filter capacitor or increasing the R_L

$\boxed{r\downarrow}$ if $\boxed{\text{Filter capacitor} \uparrow / R_L \uparrow}$

POWER SUPPLY FILTERS

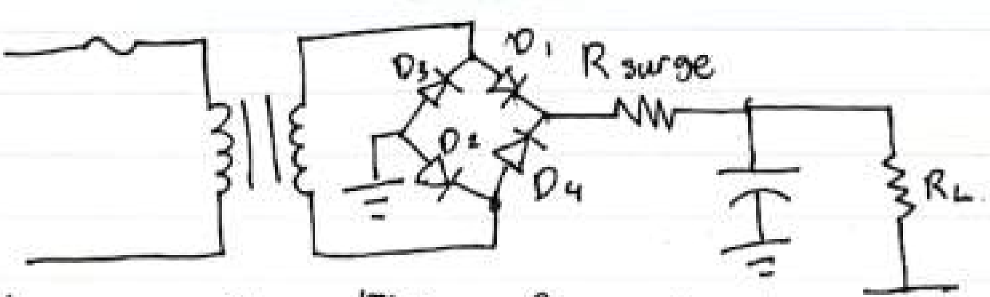
Surge Current in the Capacitor Filter

- Before the switch is closed, the filter capacitor is uncharged.
- At the instant the switch is closed, voltage is connected to the bridge and the uncharged capacitor appears as a short.
- The produces an initial surge of current Isurge through the 2 forward-biased diodes D_1 and D_2



Max surge current occurs when switch is closed at peak of input cycle.

- Thus, a surge limiting resistor is sometimes used to protect the diodes.
- The value of it must be smaller than the R_L
- Diodes must have a maximum forward surge current rating that can hold momentary surge of current — specified as I_{FSM}
- The minimum surge-limiting resistor : $R_{surge} = \frac{V_{sec(p)} - 1.4V}{I_{FSM}}$



- A series resistor Rsurge limits the surge current

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VOLTAGE REGULATOR.

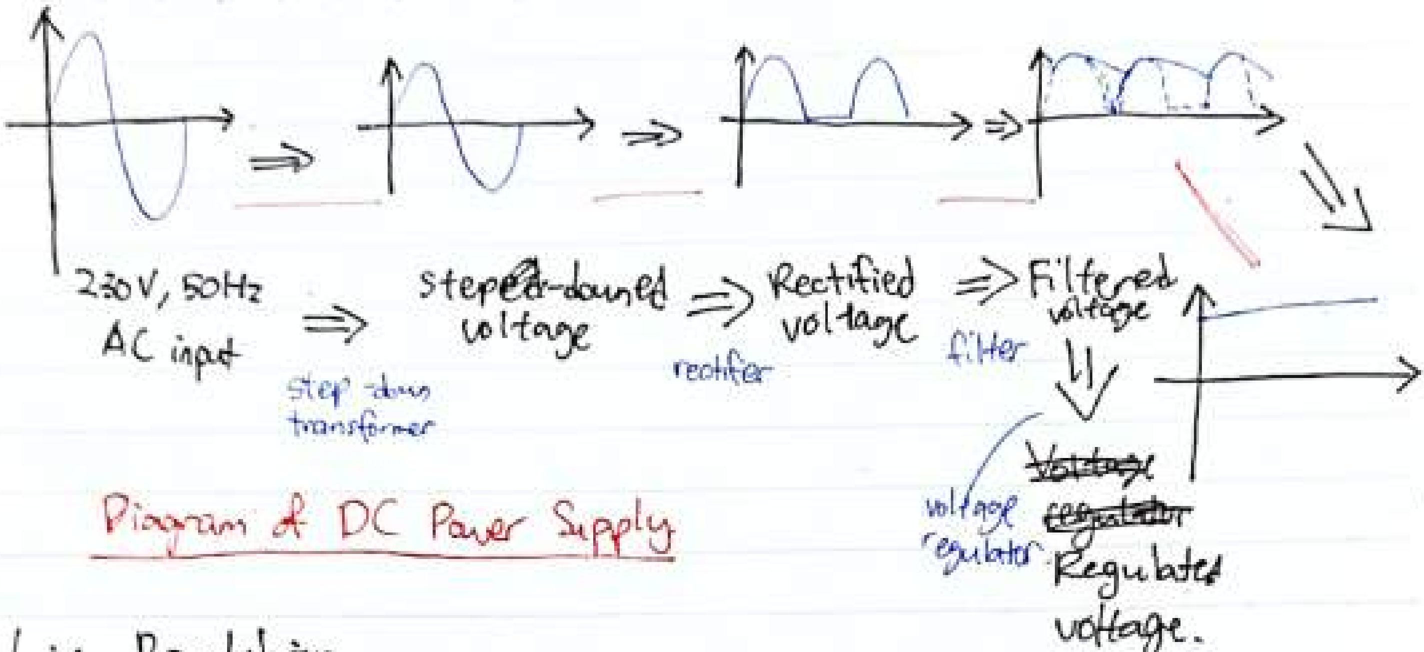

Diagram of DC Power Supply

Line Regulation.

Ability of a voltage regulator to keep it's output voltage not to have significant changes even when the input voltage has some measurable changes

→ When the dc input (line) changes, voltage regulator must maintain a nearly constant output voltage.

This is defined as the percentage change in the output voltage for a given change in the input (line) voltage

Smaller the line regulation, the better the regulator.

$$\boxed{\text{Line Regulation} = \frac{\Delta V_{out}}{\Delta V_{in}} \times 100\%}$$

Load Regulation

- When the amount of current through a load changes due to a varying R_L, the voltage regulator must maintain a near constant output voltage across the load.
- Smaller the load regulation, the better the regulator.

$$\boxed{\text{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right) \times 100\%}$$

NL = no load
FL = full load.

e.g. $V_{NL} = 12V$
$V_{FL} = 11.9V$ ↳ under 10mA
load regulation $= \frac{12 - 11.9}{11.9} \times 100\% = 0.840\%$

It can also be expressed as → load regulation $= \frac{0.840\%}{10mA} = 0.084\%/mA$

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POWER SUPPLY FILTERS

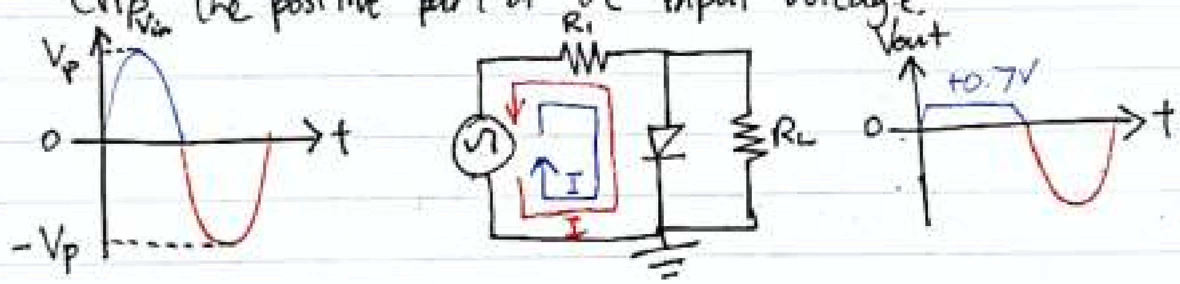
78XX IC → positive voltage output
79XX IC → negative voltage output
↳ first 2 digits ~~get~~ ~~are~~ specify the magnitude of the output voltage.

Three-terminal linear IC regulators are available to provide fixed-value output voltages & either positive / negative polarities.

DIODE LIMITING CIRCUITS

- Diode Limiting Circuits (also called limiters or clippers) are used to clip off portions of signal voltages above or below certain levels.
- 3 Main Catagories:

☆ Positive Diode Limiter
- Clip the positive part of the input voltage.



- Positive alteration → diode is forward biased.
- According to the practical diode model, when silicon diode conducts, the forward voltage across the diode is clipped at 0.7V
- ~~Positive~~ Negative alteration → diode is negative biased.
- Thus it does not conduct.
- When no current flows through the diode.

$$\boxed{I_{R_1} = I_{R_L} = \frac{V_{in}}{R_1 + R_L} \text{ and } V_{out} = I_{R_L} \times R_L = \frac{R_L}{R_1 + R_L} \times V_{in}}$$

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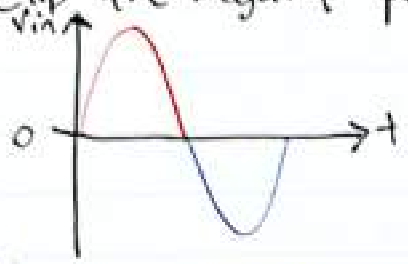
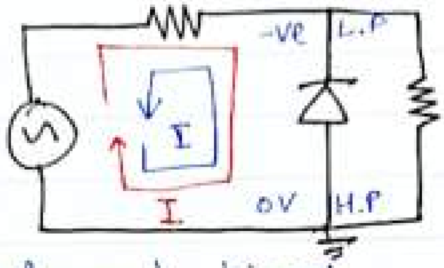
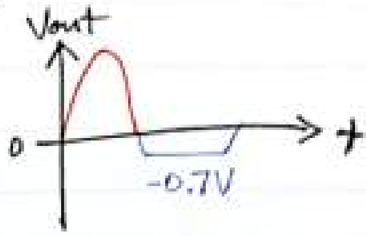
Diode Limiting Circuits.

☆ Negative Diode Limiter.

- Clip the negative part of the input voltage.







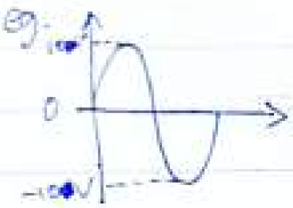
- Negative alteration → forward biased.
- When silicon diode conducts → voltage across is clipped at −0.7V
- Positive alteration → reversed biased
- Diode does not conduct

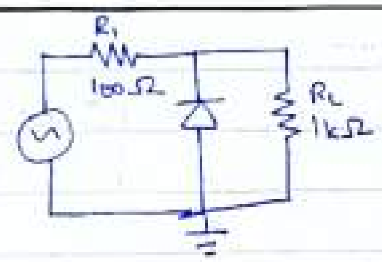
$$\boxed{V_{out} = \left(\frac{R_L}{R_1 + R_L}\right) \times V_{in}}$$

☆ If R_1 is smaller compared to R_L then $V_{out} \approx V_{in}$

---

eg:





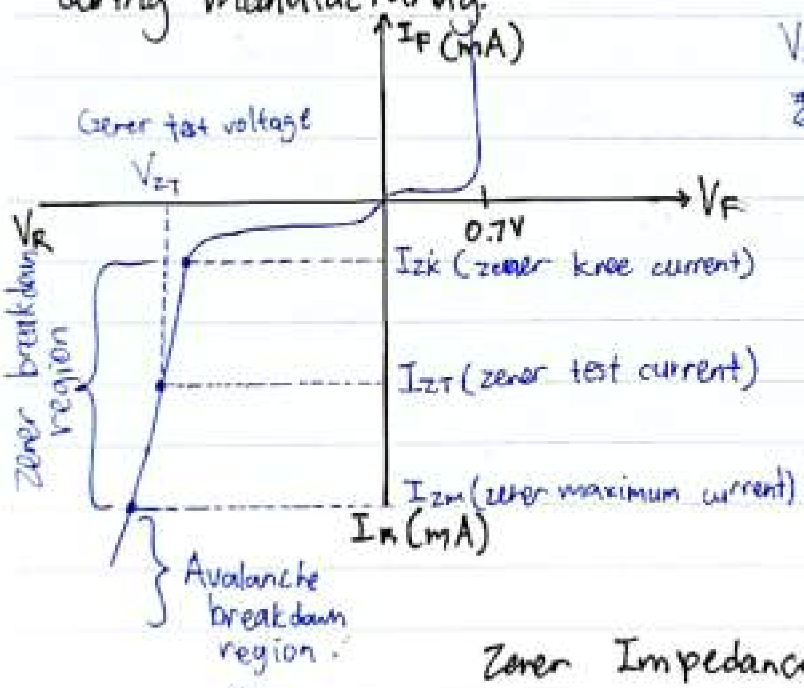
~~output~~ Vout wave :

$$V_{out} = \frac{R_L}{R_1+R_L} \times V_{in} = \frac{1}{0.1+1} \times 10 \approx 9.09V$$

ZENER DIODE.

- ~~Unlike~~ Normal p-n junction diode that are operated in a reverse-breakdown region may cause overheating and damage

- Zener diode are designed to operate in the reverse-breakdown region
- Zener diode operates like an ordinary diodes when forward biased
- They are designed to breakdown in a controlled manner at a ~~pre~~ pre-determined voltage when reversed biased.
- Once breakdown takes place, voltage across the diode is almost constant, ~~the~~ this voltage is the V_Z.
- This breakdown voltage is set by carefully controlling doping level during manufacturing.

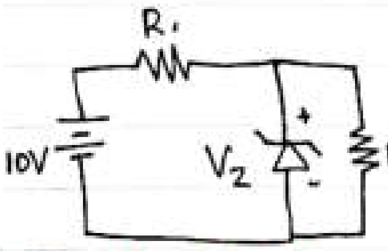


avoid this region.

zener voltage
V_Z is usually specified at I_{ZT}, and ~~Zener~~ is designated V_{ZT}.

It has 2 reverse breakdown region:
1) Zener breakdown: occurs at low reverse voltage.
2) Avalance breakdown: occurs at high reverse voltage.

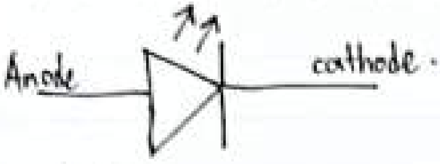
Zener Impedance:
It is defined as the change in zener voltage to the change in zener current $\boxed{Z_Z = \frac{\Delta V_Z}{\Delta I_Z}}$



In the past Zener Diodes were widely used to regulate D.C. voltages, but IC voltage ~~regul~~ regulators are now more commonly used for this purpose.

When V_{Bias} > the zener breakdown voltage, the zener diode breaks down and V_Z is the zener breakdown voltage.

LED



$\uparrow I \rightarrow \uparrow$ brightness

$\uparrow R \rightarrow \downarrow$ brightness (cuz $\downarrow I$)

Use Variable resistor to adjust brightness

LED.

- Special diode that emits light when sufficient forward current flows through it.
- When forward-biased, electrons cross the p-n junction from the n-type and recombine with holes, into the p-type.
- This release energy in the form of a little heat and mostly light.
- This process is called electroluminescence,
- Different impurities can be added during doping process to obtain different coloured light, it can also emit infrared (invisible to human eyes.)

Gallium Arsenide (GaAs) → Infrared light

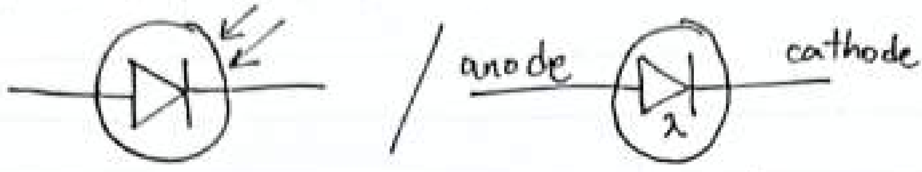
Gallium Arsenide Phosphide (GaAsP) → red / yellow.

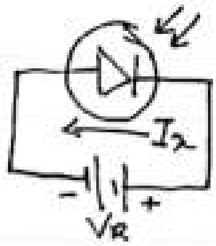
Gallium Phosphide (GaP) → ~~either~~ Red / Green.

Si & Ge are not used as they produce more heat than light.

- Forward voltage across an LED is greater than that of a diode at 1.2V to 3.2V.
- Reverse breakdown is also much less compared to junction diode at around 3V to 10V.

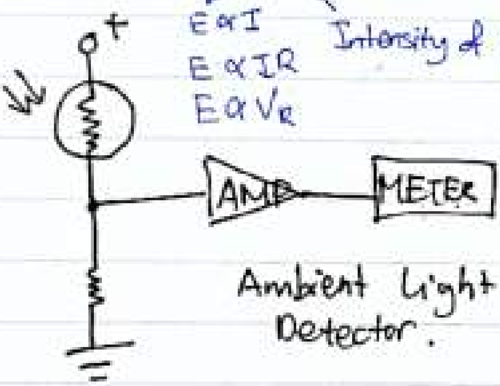
PHOTODIODE





- when light is shined → current ↑
- work on a reverse bias
- Amount of reverse current (I_λ) depends on the amount of light irradiating the photo diode.
- Sensitivity of photodiode can change
- Intensity of light measured in mW/cm^2 (irradiance) or $lumens/m^2$ (lux)

$E \propto I$
$E \propto IR$
$E \propto V_R$
Intensity of light.



Ambient Light Detector.

- The photo diode can be biased with a constant voltage across it.

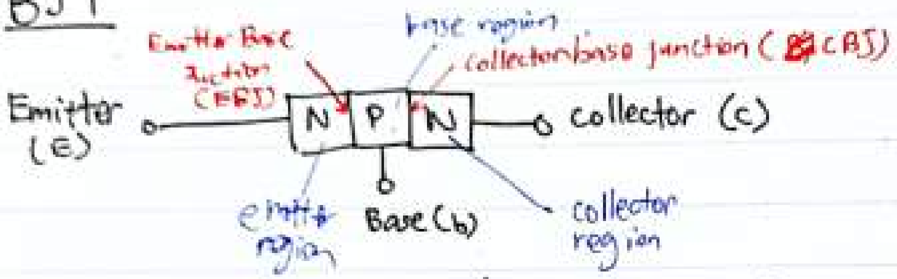
*It works in reversed-biased. At low light, the R is very high and only very ~~neg~~ small/negligible current passes through.
At high light, it's resistance drops exponentially and allows a reverse current to flow through it.

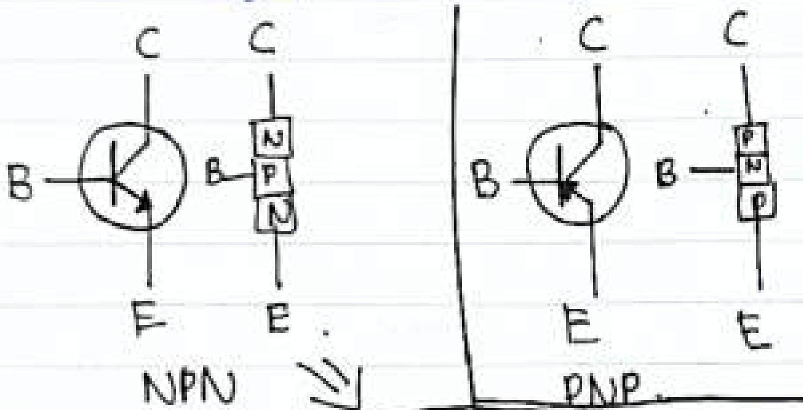
BIPOLAR JUNCTION TRANSISTOR (BJT)

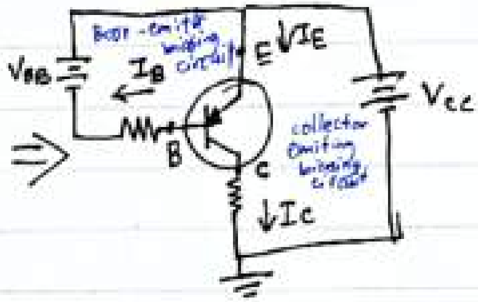
Transistors

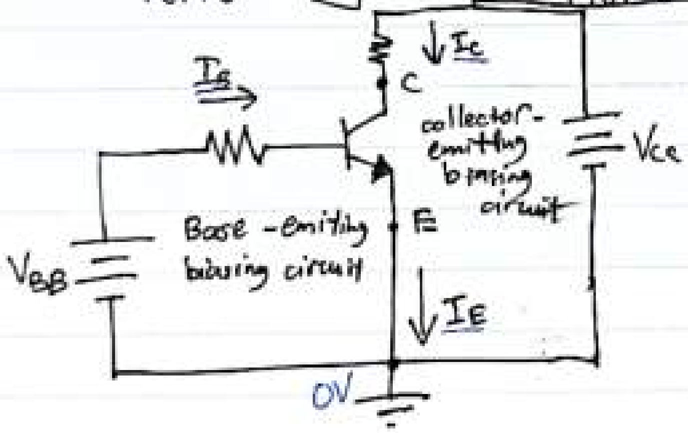
- Found in many household appline → first created in late 1940s.

BJT









$I_E = I_B + I_C$

$V_{BE} = V_B - V_E$

$V_{CE} = V_C - V_E$

$V_E = 0$

If $V_{BB} \leq 0.7V$

$V_{BE} = V_{BB}$,

$I_B = 0$.

I_B will have current if V_{BB} is greater than 0.7V

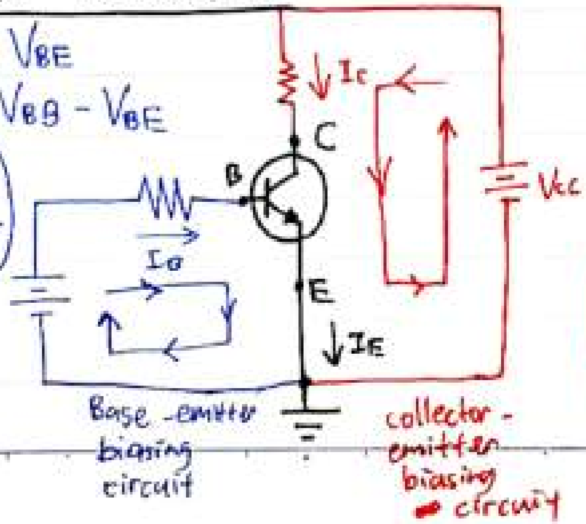
Basic Biasing Circuit Calculation

$V_{BB} = I_R \times R_B + V_{BE}$

$I_B \times R_B = V_{BB} - V_{BE}$

$$\boxed{I_B = \frac{V_{BB} - V_{BE}}{R_B}}$$

$$\boxed{I_E = I_B + I_C}$$



$V_{CC} = I_C R_C + V_{CE}$

$I_C R_C = V_{CC} - V_{CE}$

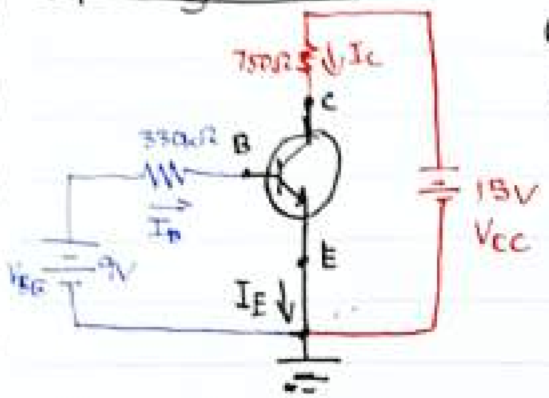
$I_C = \dfrac{V_{CC} - V_{CE}}{R_C}$

$$\boxed{I_C = -\frac{1}{R_C} V_{CE} + \frac{V_{CC}}{R_C}}$$

Load line equation

BIPOLAR JUNCTION TRANSISTOR (BJT)

Operating Point



Operating point or Q-point (Quiescent point) is the V_{CE} and I_C of the biasing circuit

$V_{CC} = I_C R_C + V_{CE}$

$I_C = -\frac{1}{R_C} V_{CE} + \frac{V_{CC}}{R_C}$ Load Line Equation

$I_C = -\frac{4}{3} V_{CE} + 20 (mA)$

$\left(0, \frac{V_{CC}}{R_C}\right) = \left(0, \frac{15V}{0.75k\Omega}\right) = (0, 20mA)$ y-intercept

$(V_{CC}, 0) = (15V, 0)$ x-intercept

$V_{BB} = 9V > 0.7V$

0.7V is the knee voltage of a p-n junction

B-E junction conduct

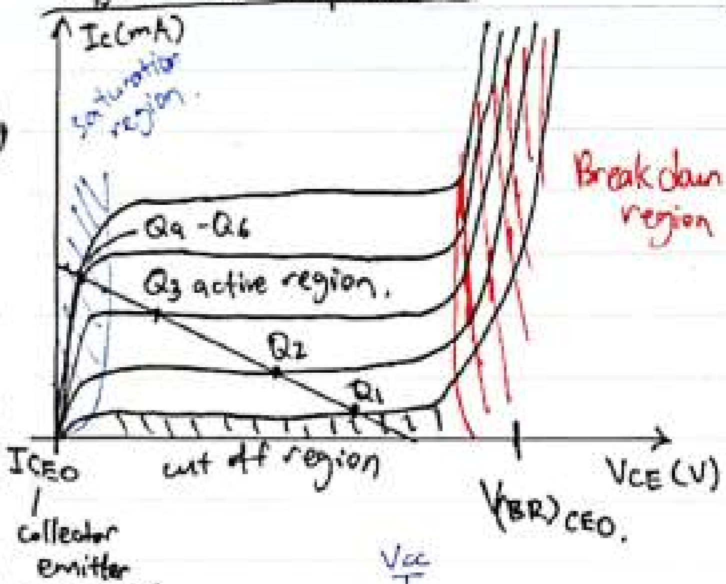
$V_{BE} = 0.7V$

$V_{BB} = I_B R_B + V_{BE}$

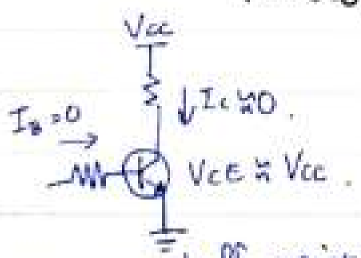
$9V = I_B \times 330k\Omega + 0.7V$

$I_B = \frac{9-0.7}{330k\Omega} = 25\mu A$ } $I_B = \frac{V_{BB} - V_{BE}}{R_B}$

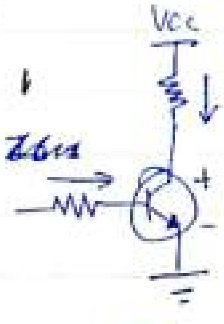
Region of Operation



Q-point	Region	I_B, I_C	$V_{CE} = V_{CC} - I_C R_C$
Q_1	cut off	$I_B = 0$. $I_C \approx 0$	~~$V_{CE} \approx V_{CC} - 0 \cdot R_C$~~ $V_{CE} \approx V_{CC}$
Q_2, Q_3	active region	$I_C \propto I_B$	$0.2V < V_{CE} < V_{CC}$ or $0.3V$
$Q_4 - Q_6$	Saturation	~~$I_C \propto I_B$~~	$V_{CE} = 0.2V/0.3V$



cut-off region



$I_C = \frac{V_{CC} - V_{CE}}{R_C}$

$V_{CE} = 0.2V$ or 0.3

Saturation region

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Date

- When a transistor is biased in the cut off region, the transistor operate as an open switch. $I_B = 0$; $I_C \approx 0$ and $V_{CE} \approx V_{CC}$
- When a transistor is biased in the active region, ~~the transistor~~ it operates as a current amplifier. $I_C = \beta I_B$; $V_{CE} = V_{CC} - I_C \times R_C$; and $V_{CE(sat)} < V_{CE} < V_{CC}$, where $V_{CE(sat)} = 0.2V$ or $0.3V$
- When a transistor is biased in the saturation region, it operates as a closed switch. $I_C / I_B < \beta$; $I_C = (V_{CC} - V_{CE(sat)}) / R_C$; $V_{CE} = V_{CE(sat)}$

$$\beta = \frac{\text{collector current}}{\text{Base current}} = \frac{I_C}{I_B}$$

When $I_B = I_{B(min)}$
- In both active and saturation region.
- $I_C = \beta I_B$
- $I_C = I_{C(sat)}$
- $V_{CE} = V_{CE(sat)} = 0.2V$ or $0.3V$.

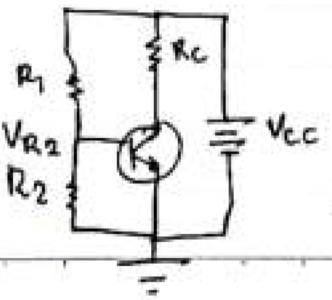
Thus,
- $\beta I_{B(min)} = I_{C(sat)}$
- $I_{B(min)} = \frac{I_{C(sat)}}{\beta}$

where $I_{B(min)}$ is the minimum base current to bias the transistor to saturation.

When $I_B > I_{B(min)}$
- In saturation region only
- $I_C \neq \beta I_B$
- $I_C = I_{C(sat)}$
- $V_{CE} = V_{CE(sat)} = 0.2V$ or $0.3V$
- $I_{B(min)} = \frac{I_{C(sat)}}{\beta}$

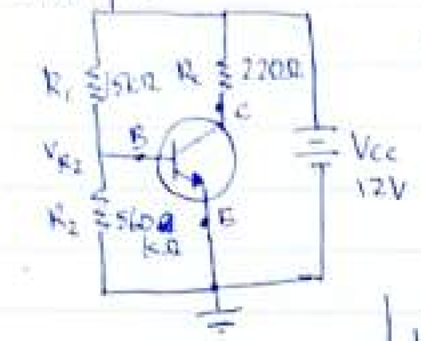
- To ensure deep saturation, set $I_B = 2 I_{B(min)}$

$$\boxed{\frac{R_2}{R_1 + R_2} \times V_{CC} = V_{R2}}$$



BIPOLAR JUNCTION TRANSISTOR (BJT)

Example.



a) find I_B, I_C & V_{CE} when $\beta = 150$ and $V_{CE(sat)} = 0.2V$

$$\frac{R_2}{R_1+R_2} \times V_{cc} = \frac{0.56}{15+0.56} \times 12 \approx \underline{0.43 \rightarrow < 0.7V}$$

cut off region.

$\therefore I_B = 0,\ I_C \approx 0$, and $V_{CE} \approx 12V$

b) If R_2 is changed to $1.2k\Omega$

$$\frac{1.2}{15+1.2} \times 12 \approx \underline{0.9V \rightarrow > 0.7V}$$

not off, and $V_{BE} = 0.7V$

$$I_{C(sat)} = \frac{V_{cc} - V_{CE(sat)}}{R_C} = \frac{12-0.2}{0.22} \approx 53.6mA$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta} \approx \frac{53.6}{150} \approx 0.36mA$$

$$I_B = I_{R_1} - I_{R_2}$$

$$I_B = \frac{V_{cc} - V_{R_2}}{R_1} - \frac{V_{R_2}}{R_2} = \frac{12-0.7}{15} - \frac{0.7}{1.2} \approx 0.17mA_{//}$$

$\therefore \underline{I_B \approx 0.17mA < I_{B(min)} \approx 0.36mA}$.

active region.

$$I_C = \beta I_B \approx 150 \times 0.17 \approx 25.5mA_{//}$$

$$V_{CE} = V_{cc} - I_C R_C \approx 12 - 25.5 \times 0.22 = 6.39V_{//}$$

c) If $R_2 = 18k\Omega$.

$$\frac{18}{15+18} \times 12 = \underline{6.55V > 0.7}$$

not off and $V_{BE} = 0.7V$

$$I_{C(sat)} = \frac{12-0.2}{0.2} \approx 53.6mA$$

$$I_{B(min)} = \cancel{\frac{I_{C(sat)}}{\beta}} \approx \frac{53.6}{150} \approx 0.36mA.$$

$$I_B = \frac{12-0.7}{15} - \frac{0.7}{18} \approx 0.7144mA_{//}$$

$\therefore \underline{I_B \approx 0.71 > I_{B(min)} \approx 0.36}$

saturation region.

$V_{CE} = V_{CE(sat)} = 0.2V_{//}$

$$I_C = I_{C(sat)} = \frac{12-0.2}{0.22} \approx 53.6mA_{//}$$

$\boxed{I_C \neq \beta \times I_B \text{ in Saturation Region}}$ ☆

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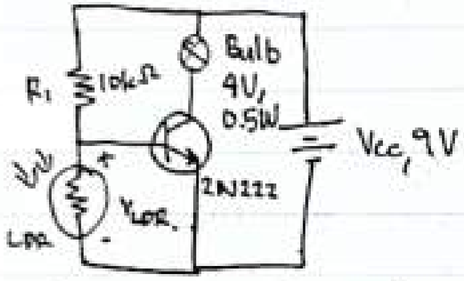
TRANSDUCER.

~~LDR~~ Converts energy from one form to another

LDR

light intensity $\propto \frac{1}{R}$ (decreases R when light increases)

When connected with a BJT, can turn to a automatic lighting circuit



R_{LDR} = 5kΩ at 50lux to 1kΩ at 500lux

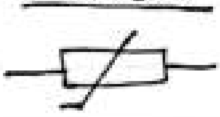
☆ when $\frac{R_{LDR}}{R_1 + R_{LDR}} \times V_{cc} \leq 0.7$, $I_B = 0$, transistor go off, and bulb go off.

☆ when $\frac{R_{LDR}}{R_1 + R_{LDR}} \times V_{cc} > 0.7$, $V_{BE} = 0.7V$, $I_B = \frac{V_{cc} - 0.7}{R_1} - \frac{0.7}{R_{LDR}}$

Saturation Region

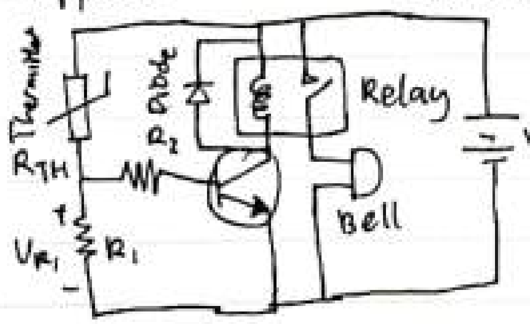
☆ Light Intensity ↑, R_{LDR} ↓, I_B ↓, I_C ↓, Bulb Brightness ↓

Thermistor



- Semiconductor that varies it's resistance with temperature.
- Temp ↑, R ↓
- sensitivity at about -4% /°C (-ve co.eff of temp).
- Range of -50°C to +300°C

Appication: Fire alarm.



☆ No fire, R_{TH} very high and $\frac{R_1}{R_{TH}+R_1} \times V_{cc} < 0.7V$

$\therefore I_B = 0$ & $I_C = 0$.

- Relay not energized, and stay in normal open state
- Bell off.

- When fire breaks out, R_{TH} drops and $\frac{R_1}{R_{TH}+R_1} \times V_{cc} > 0.7V$

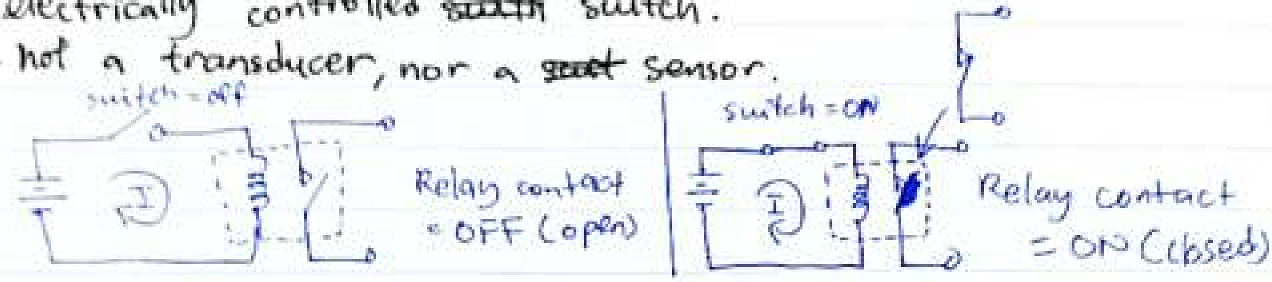
$\therefore I_B > 0$ and $I_C > 0$.

- Relay energized and close the relay → bell on.

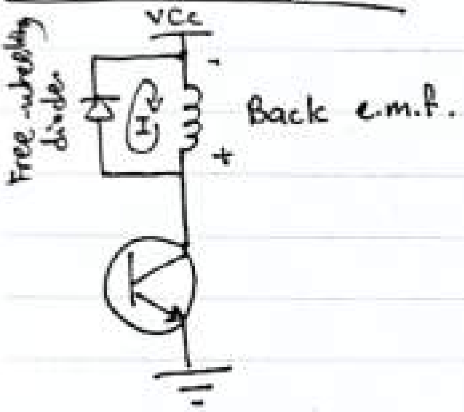
TRANSDUCER

Relay

- electrically controlled ~~swith~~ switch.
- not a transducer, nor a ~~sent~~ sensor.



Free-wheeling diode

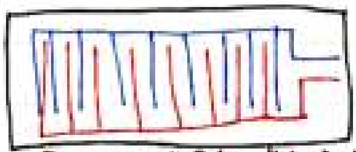


When the transistor ~~s~~ switches off, there is a collapse in the magnetic field around the relay coil. This causes a back E.M.F. to be induced across the coil. The energy can now be retured to the circuit through it. This prevents the transistor from being ~~b~~ damaged.

When no free-wheeling diode high current surge discharged through the transistor. This may damage the transistor.

Moisture Sensor

- Operates on principle that water is a better conductor of electricity compared to air.
- Resistance ~~Be~~ between the moisture sensor contacts changes in the following manner.
  - High resistance (open circuit) when dry.
  - Low resistance when ~~wt a~~ wet.



Simple PCB Moisture Sensor

- ~~Avdaw~~ Advantages of using Output Relay
  - Separated high output power supplies can be used for demanding loads
  - Separated AC supplies can be used for AC loads.

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☆ LDR → R↓ ~~var~~ non-linearly with light intensity
☆ Thermistor → R↓ exponentially with temperature
☆ Moisture sensor → resistance decreases with moisture level.
☆ A BJT circuit can be used to detect the changes in the sensor resistance and change the collector current accordingly.
☆ A relay can be controlled by a sensor circuit and can be used to power up a demanding load or an AC load with an insulated power source.
☆ A free-wheeling diode connected to a relay and a transistor protects the transistor from the induced surge current when the transistor switches ON to OFF.

$\Delta I_Z = I_Z - I_{ZT}$ $\qquad I_T = \frac{V_T - V_Z}{R}$.

$\Delta V_Z = \Delta I_Z \times Z_Z$. $\qquad I_L = I_T - I_Z$. $\qquad$ ~~$I_C = \frac{V_{CC} - V_{CE}}{R_C}$~~

$V_Z = \Delta V_Z + V_{ZT}$ $\qquad R_L = \frac{V_Z}{I_L}$

Automatic fire alarm circuit.

No fire → R_{TH} high, V_B = low.

$V_{BE} < 0.7V$, transistor = cut off.

$I_C = 0$ → relay coil not magnetized.

relay contact → open.

Bell → off

Fire break out → R_{TH} = low, V_B = high

$V_{BE} = 0.7$, transistor = active. → saturation.

I_C = flows, → relay coil magnetized

relay contact → closed.

Bell → on.

Alt.

No fire → R_{TH} very high, $\frac{R_1}{R_{TH}+R_1} \times V_{CC} = V_{R_1} < 0.7V$

$I_B = 0$ & $I_C = 0$.

Relay not energized, contact open.

Bell off.

fire Break out → R_{TH} very low, $\frac{R_1}{R_{TH}+R_1} \times V_{CC} = V_{R_1} > 0.7V$

$I_B > 0$ & $I_C > 0$

Relay will be energized, contact closed.

Bell on.

Q point	Region	I_B, I_C	$V_{CE} = V_{CC} - I_C R_C$.
Q_1	Cutoff	$I_B = 0$, $I_C \approx 0$	$V_{CE} \approx V_{CC}$
Q_2, Q_3	Active	$I_B \propto I_C$	$0.2/0.3 < V_{CE} < V_{CC}$
$Q_4 - Q_6$	Saturation	$\times$	$0.2/0.3 = V_{CE}$

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$$P = IV.$$

$$P = I^2 R.$$

$$P = \frac{V^2}{R}.$$

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Operational Amplifier Fundamentals

Characteristics of an op-amp:
- The need for an amplifier,
- amplification (gain),
- bandwidth,
- input & output impedances, and
- distortion.

Amplifiers

- When watching the TV, you increase the volume if you are unable to hear it.
- When the picture on the TV gets too dark, you increase the brightness
- In both cases, you are taking a ~~relatively~~ relatively weak signal and making it stronger (increasing its power).
- The process of increasing the amplitude or power of a signal is called amplification.
- A circuit used to perform this function is called an amplifier.
- The most common types of amplifiers: * Voltage amplifier,
  * Current amplifier,
  * Power amplifier.

Ideal amplifier characteristics

- Infinite Voltage → $A_v = \infty$
- Infinite input impedance → $Z_{in} = \infty$
- zero output impedance → $Z_{out} = 0$
- Infinite bandwidth, → $BW = \infty$
- zero distortion (Input / Output relationship being linear) (Vo is proportional to Vi)
- Infinite Gain → $A_v = \infty$

Gain

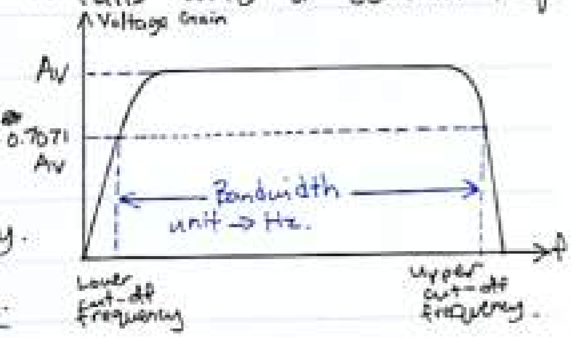
- Amplifiers are circuits that exhibit a property called gain.
- The gain of an amplifier is a multiplier that exists between the input and output.
- An amplifier has a $A_v = 100 \rightarrow V_{out}$ will be 100X larger than V_{in}.
- The gain of an amplifier is determined by the amplifier's circuit component value.

$A_v = \frac{V_{out}}{V_{in}}$

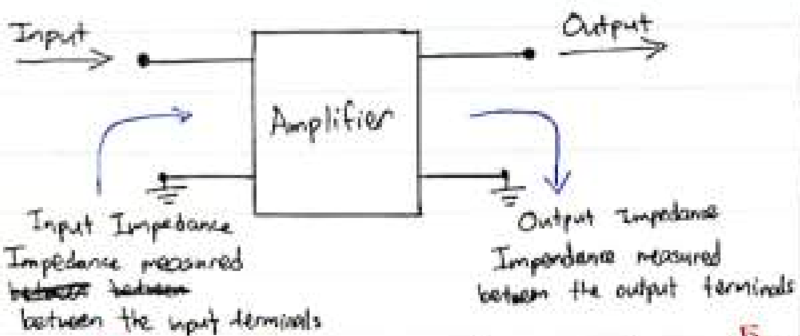
$V_{out} = A_v V_{in}$

Band-width

- The gain of the amplifier is not uniformed - it falls after a certain frequency.
- The range of frequencies over which a useful gain is available is called the bandwidth of the amplifier.
- Difference between upper and lower cutoff frequency.
- Freq. in should be higher than the lower cut-off freq. and lower than the upper cut-off freq.
- Bandwidth of an amplifier depends on the circuit component values and the type of active component(s) used.



Impedance (In & Out / Zin & Zout)



Volt diff in the input divided by the input current

Impedance is not a signal, it is a resistance - like property.

Volt diff in ~~the~~ the output, divided by the output current

- Impedance is resistance - like property used in AC circuits
- An AC signal comes with the ~~parameters~~ parameters of frequency and phase.
- ∴ Impedance is also a function of frequency and phase.

Recall:

$Z_R = R\,\Omega$

$Z_C = \frac{1}{\omega C} \angle -90^\circ \Omega$

$Z_L = \omega L \angle 90^\circ \Omega$

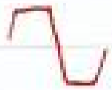
Operational Amplifier Fundamentals

Distortion

- The input signal and the output signal must retain the same shape
- It has a linear input and output relationship
- If the shape of the output signal does not resemble the input signal, the output signal is distorted - this is undesirable.

✓ may have diff amplitude and or phase → same shape = not distored.

Sine wave in → Sine wave out.

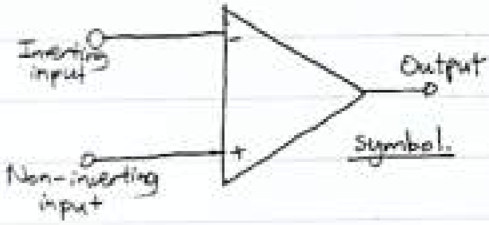


✗ not same shape = distored

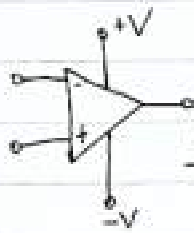
Op - Amps

- Early op-amps are used to perform math operations - e.g. addition, substration, intergation and differentiation - hence the term "operational".

Symbols and terminals



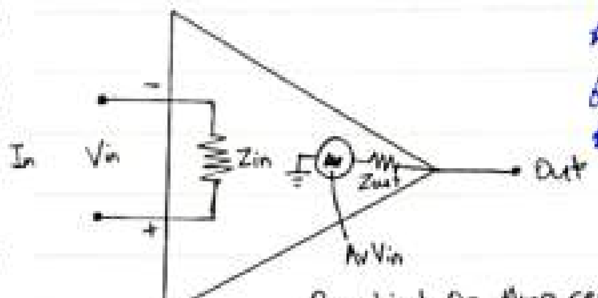
symbol.



symbol with dc supply connection

- It comes in DIP (Dual In-line package) and SMT (Surface-Mount Technology).

The practical Op-Amps



Practical Op-Amp representation.

★ High V gain ★ Low Zout
★ High Zin ★ Wide BW.

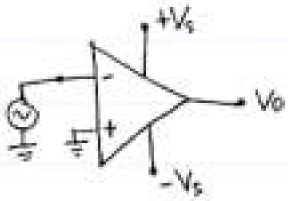
- p-p Vout usually limited to slightly less than the two supply voltages.
- Iout also limited by the internal restrictions such as power dissipation and $\underbrace{\text{component rating}}_{\text{e.g. max power rating.}}$

Op-Amp Input Modes.

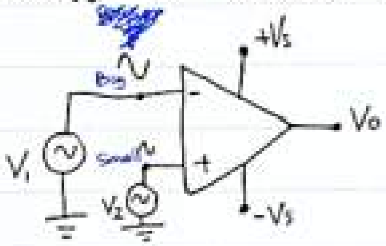
Modes of Signal Operation

Op-Amp circuits use one of the 3 basic input modes of operation:

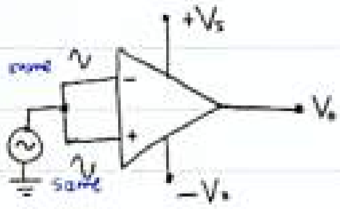
1. Single-ended input mode has one input connected to the input signal and the other connected to ground.



2. Differential input where the inputs are connected to different signal sources.



3. Common-mode input, where both inputs are connected to the same signal source.



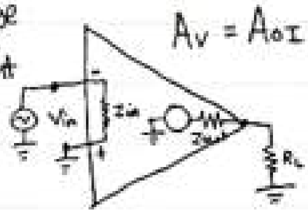
Saturated Output Voltage

- The limit on the output voltage is set by the supply voltages, $+V_s$ and $-V_s$
- The upper limit is called the positive saturation voltage, $+V_{sat} \approx +V_s - 1V$.
- The lower limit is called the negative saturation voltage, $-V_{sat} \approx -V_s + 2V$.
- e.g. a supply voltage of $\pm 15V$, $+V_{sat} \approx +14V$ and $-V_{sat} \approx -13V$.
  Therefore, V_o is restricted to a symmetrical p-p swing of $\pm 13V$//.

Op-Amp Open Loop Voltage Gain (A_{OL})

- The open-loop voltage gain of an op-amp is the internal voltage gain of the device and represents the ratio of output voltage to input voltage when output signal is not feedbacked to the inputs. i.e. when output pin is not connected to any of the input pins through any wire or components.

$A_v = A_{OL}$ = Open Loop Gain.

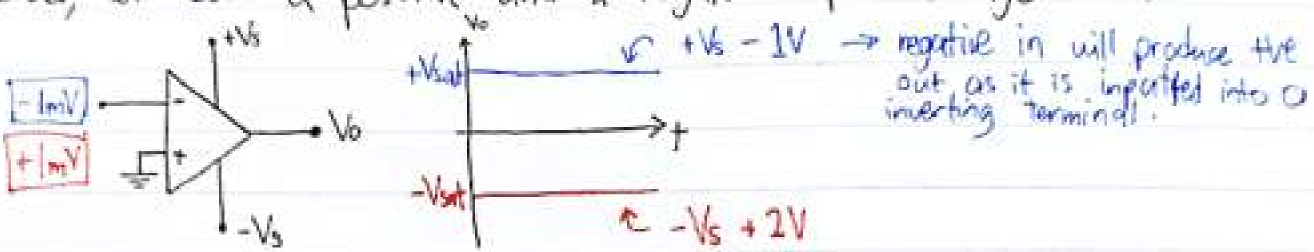


- The open-loop ~~volt~~ voltage gain is set entirely by the ~~...~~ internal design.
- Typical open-loop voltages is usually larger than 100,000.
- Data sheets often refer to the open-loop voltage gain as the large-signal voltage gain.

Operational Amplifier Fundamentals

Disadvantages of Open Loop Op-Amp

- Extremely small input voltage drives the op-amp to saturation.
  e.g. $V_{IN} = 1mV$ and $A_{ol} = 100,000$, then $V_{OUT} = V_{IN} A_{ol} = (1mV)(100000) = 100V$
- Since the output level of an op-amp can never reach 100V, it is driven deep into saturation and the output is limited to its maximum output levels, for both a positive and a negative input voltage of 1mV.



- When the voltage at the non-inverting terminal (+ve) is higher than the voltage at the inverting terminal (-ve), then the output voltage will be a positive value.
- When the voltage at the non-inverting terminal (+ve) is lower than the voltage at the inverting terminal (-ve), then the output voltage will be a negative value.
- When the input is applied to the inverting terminal of an op-amp, then the op-amp will have a negative gain (opposite).
- The extremely high open loop gain of an op-amp creates an unstable situation.
  - Small input noise voltage amplified such that amplifier is driven out of the linear region
  - Can also cause unwanted oscillations.
- Open-loop gain parameter of an op-amp can vary greatly from one device to another. It is not well - controlled parameter during manufacturing.

Why Use Negative Feedback?

- The main disadvantages of an open-loop op-amp are caused by it's extremely high open-loop gain.
- Negative feedback creates an effective reduction in gain by taking a portion of the output and applying it back to the inverting terminal.
- Closed-loop gain is usually much less than the open-loop gain and can be controlled by the external components connected to the op-amp.

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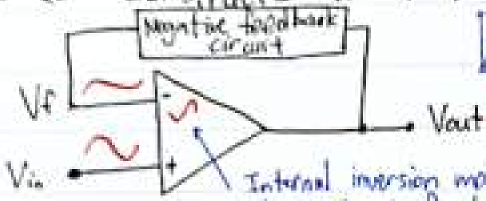
Op-Amp with Negative Feedback

- Negative feedback is one of the most useful concepts in electronics, esp in op-amp "application"
- Negative feedback is the process whereby a portion of the output voltage of an amplifier is ~~return~~ returned to the input with a phase angle that opposes (or substracts from) the input signal.



$\boxed{V_{out} = (V_{in} - V_f) \times A_{ol}}$

Internal inversion makes V_f 180° out of phase with Vin, thus reducing Vout and effectively reducing the gain.

Since output is feedback to the inverting terminal, higher the output, higher the V_f and lower the $(V_{in} - V_f)$ difference as a result, Vout will reduce and prevent from saturation.

- In addition to providing a controlled, stable voltage gain, negative feedback also ~~provi~~ ~~prot~~ provides for control of the input and output impedances and amplifier band width.

	Voltage Gain	Input Impedance	Output Impedance	Band width
Without Feedback	$A_v = A_{ol}$ is too high for linear amplifier applications.	Relatively high	Relatively low	Relatively narrow (because the gain is so high).
With negative feeback.	A_{cl} is set to desired value by the feedback circuit	Can be increased or reduced to a desired value depending on the type of circuit	Can be reduced to a desired value	Significantly wider

$A_{cl} = A_{closed\text{-}loop}$

$A_{ol} = A_{open\text{-}loop}$

With negative feedback, the closed-loop voltage gain (A_{cl}) can be reduced and controlled so that the op-amp can function as a linear amplifier.

Non-Inverting Amplifiers

Introduction

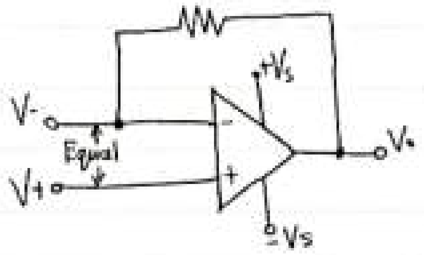
- Non-inverting and inverting amplifier are ~~different~~ the 2 basic config. of an operational amplifier. Negative feedback is applied in both configurations to provide linear operation and undistorted output.
- In a non-inverting amplifier, the input signal is applied to the non-inverting terminal of an op-amp; whereas in a inverting amplifier, the input signal is applied to the inverting terminal through an input resistor.
- Another difference between a non-inverting amplifier and an inverting amplifier is that the output signal of a non-inverting amplifier is in phase with the input signal, but the output signal of an inverting amplifier is out of phase with the input signal.

Non-Inverting ~~Amplifier~~ Amplifier.

Input Voltages of Op-Amp with Negative Feedback, $V_+ \simeq V_-$

- With negative feedback, the op-amp operates in the linear region. Therefore,
  - $V_{OUT} = (V_+ - V_-) \times A_V$

    V_- and V_+ are the input voltage at the inverting and non-inverting terminals.
  - $-V_{sat} \leq V_{OUT} \leq +V_{sat}$
- $\because$ A_V is very large
- $\therefore$ The difference $(V_+ - V_-)$ must be very small. Therefore
  - $V_+ \approx V_-$
  - This is an important appoximation when analysing op-amp circuits with negative feedbacks.



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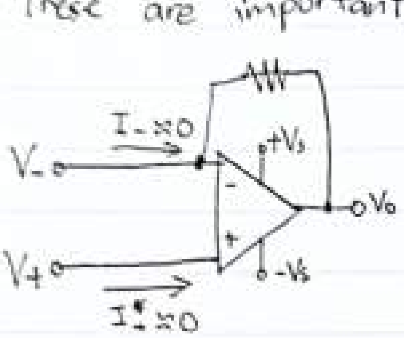
Input Current to Op-Amp is Zero.

- The input Impedance of an op-amp is very high. It can be found in the range of ~$1M\Omega$ to $1T\Omega$. Therefore,
  - $Z_{in} \approx \infty$
  - $I_- \approx 0$ and $I_+ \approx 0$, ie, no input current flowing into the op-amp.
  - These are important approximations when analysing op-amp circuits.



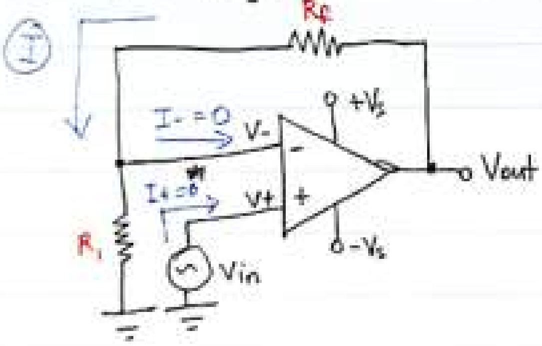
Non - Inverting Amplifier.

- Assume ideal op-Amp is used, since the input current to the ~~op-amp~~ ~~op-amp~~ op-amp = 0, the same current that flows through R_f will also flow into R_i.

$$V_{out} = IR_i + IR_f = I(R_i + R_f)$$

- Due to negative feedback, $V_+ = V_-$ | - Since $V_+ = V_{in}$ and $V_- = IR_i$

$$V_{in} = IR_i$$



- Hence, $A_{cl} = \frac{V_{out}}{V_{in}} = \frac{I(R_i + R_f)}{IR_i} = \frac{R_i + R_f}{R_i}$

$$= 1 + \frac{R_f}{R_i}$$

- The closed loop voltage gain of ~~an~~ a non-inverting amplifier is
- The voltage gain is positive. It indicates that the output signal is in phase with the input signal.
  - $V_{out} = \left(1 + \frac{R_f}{R_i}\right) V_{in}$
  - $Z_{in} = \frac{V_{in}}{I_i} = \frac{V_{in}}{I_+} \rightarrow \infty$ Where the Z is the impedance of the whole non-inverting amplifier.
  - $Z_{out} = 0$ (Assume ideal op-amp ~~used~~ used. Proof is not provided.)

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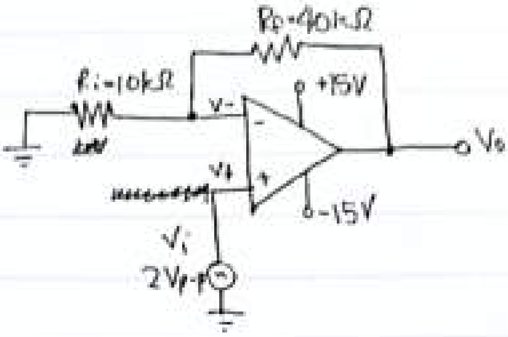
Non-Inverting Amplifiers

a) Calculate Voltage gain, A_V.

b) Calculate the output voltage $V_{o(p-p)}$

c) Sketch output voltage wave, and show the phase relationship

d) Sketch the output wave if the value of R_f is firstly changed to 90kΩ and later changed to 190kΩ.



SOLUTIONS

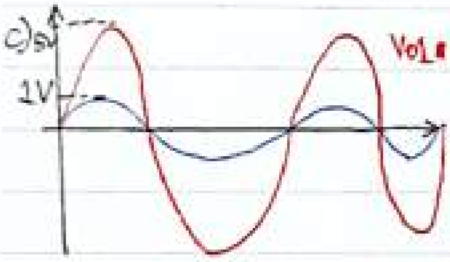
a) Voltage Gain,

$A_{cl} = 1 + \frac{R_f}{R_i} = 1 + \frac{40}{10} = 5$ //

b) The output voltage,

$V_o = A_{cl} \times V_i = 5 \times 2 = 10V_{p-p}$.

c)



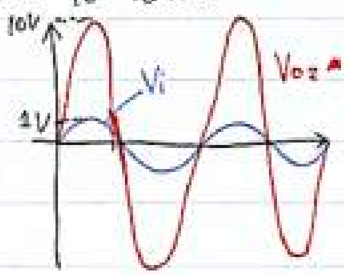
d) R_f change from 40kΩ to 90kΩ

The voltage gain,

$A_{cl} = 1 + \frac{90}{10} = 10$

The output voltage,

$V_o = 10 \times 2 = 20V_{p-p}$



R_f changes from 90kΩ to 190kΩ

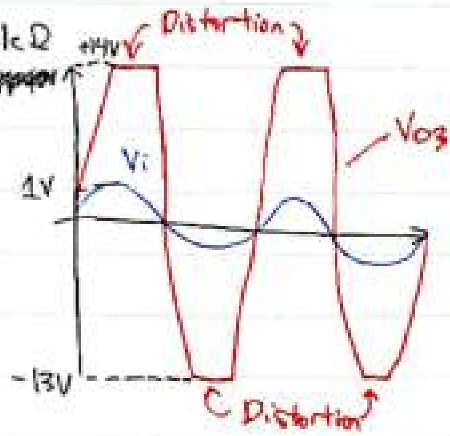
The voltage gain,

$A_{cl} = 1 + \frac{R_f}{R_i} = 1 + \frac{190}{10} = 20.$

The output voltage,

$V_o = 20 \times 2 = 40V_{p-p}$

exceeded the max voltage which is max 30Vp-p thus it will clip. (distorted)

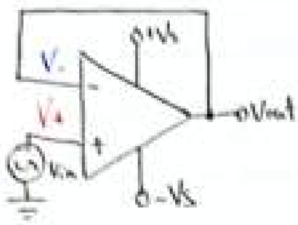


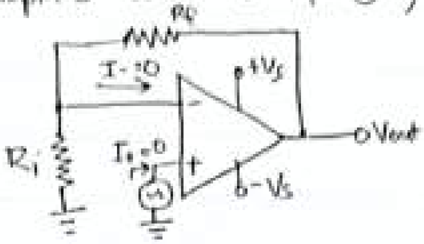
why +14V & -13V? Because the output voltage is forced into saturation causing the output waveform to be distorted

where $V_s = \pm 15V$, $+V_{sat} \approx +V_s - 1V$ and $-V_{sat} \approx -V_s + 2V$

<u>Voltage Follower</u>

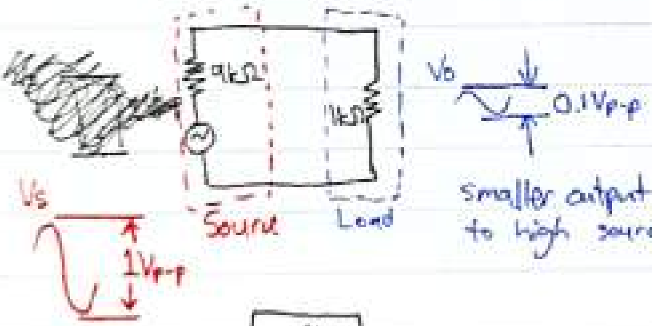
- This is a special case of non-inverting amplifier where → $R_f = 0$, $R_1 = \infty$



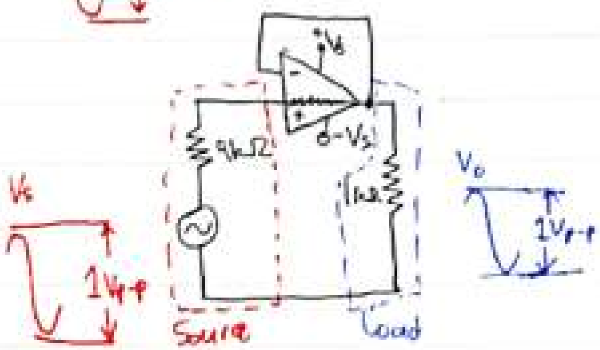


- Due to the extremely large voltage gain of an op-amp, the differential input voltage is zero. when there is a -ve feedback loop. Therefore,
  $V_+ = V_-$

- Since $V_{in} = V_+ = V_- = V_{out}$ - Voltage gain of voltage follower is $A_v = 1$
- For Voltage follower, $V_{in} = V_{out}$
- Characteristics:
  • Extremely high input impedance • Extremely low output impedance
  • Capable of driving a relatively low resistive load due to its very small output impedance.
  • Often used as buffer circuit to match a high internal resistance signal source to a low resistive load.



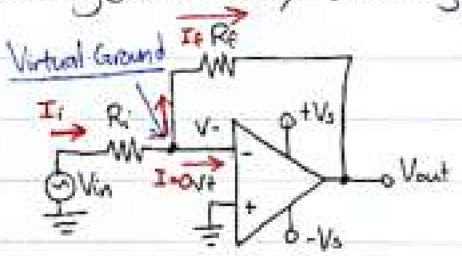
smaller output voltage due to high source resistance.



Inverting Amplifiers

Introduction to Inverting Amplifiers

- Inverting amplifier and non-inverting amplifier are the two basic configuration of an op-amp. Negative feedback is applied in both configurations to provide linear operation and undistorted output.
- In a non-inverting amplifier, the input signal is applied to the non-inverting terminal of the op-amp; whereas in an inverting amplifier, the input signal is applied to the inverting terminal through an input resistor. Another major difference between the 2 amplifiers is that the output signal of a non-inverting amplifier is in phase with the input signal but the output signal of an inverting amplifier is 180° out of phase with the input signal.
- Some variations of the inverting amplifiers are used to perform math operations, such as summing(addition), scaling & averaging.



- Assume ideal op-amp is used.
- With negative feedback applied,
  $V_- = V_+$
- Since V_+ is connected to gnd, V_- will also be at gnd potential.
- As V_- is not physically connected to the gnd. unlike V_+, it is refered to as a Virtual Ground ← 0V
- Current flowing through R_i is : $I_i = \frac{V_{in} - 0V}{R_i} = \frac{V_{in}}{R_i}$
- Current flowing through R_f is : $I_f = \frac{0 - V_{out}}{R_f} = \frac{-V_{out}}{R_f}$
- Since no current flows into the input terminals, I_i fully flows into the feedback resistor R_f, Thus, $I_i = I_f \Rightarrow \frac{V_{in}}{R_i} = \frac{-V_{out}}{R_f} \Rightarrow \boxed{A_{cl} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}}$
  - The negative sign in the expression denotes that the output signal is 180° out-of-phase with the input signal. → Output Voltage ⇒ $V_{out} = -\left(\frac{R_f}{R_i}\right) V_{in}$
- Input Impedance of the inverting amplifier is = $Z_{in} = \frac{V_{in}}{I_i} = R_i$
- The output impedance of an inverting amplifier is
  Z_{out} = internal output impedance of op-amp // R_f.
  - Proof is not provided.

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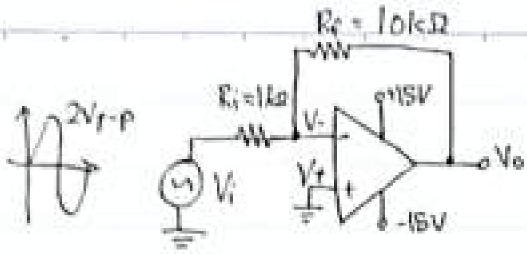
Example.



a) Find $V_{o(p-p)}$

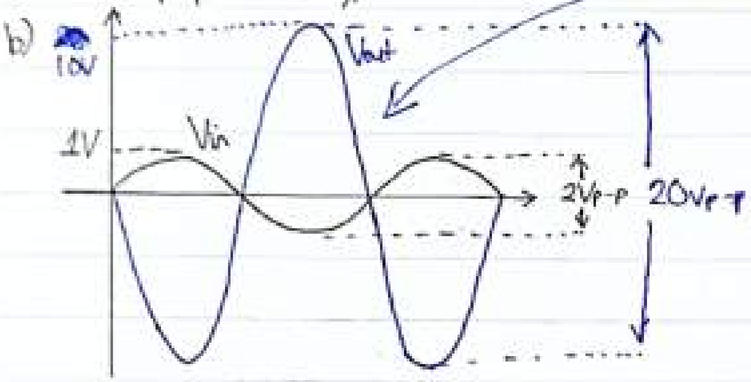
b) Sketch in & out waveforms, and

c) out waveform if the amplitude of the Vin is doubled.

a) $V_{out} = -\left(\frac{R_f}{R_i}\right)V_{in} = -\left(\frac{10k\Omega}{1k\Omega}\right)2V_{p-p} = \underline{-20V_{p-p}}$ → 180° out-of-phase

$\therefore V_{o(p-p)} = 20V$

b)



c)

$+V_{sat} = 15-1 = \underline{14V}$

$-V_{sat} = -15+2 = \underline{-13V}$

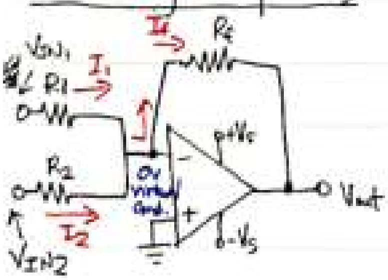
$V_{out} = -\left(\frac{R_f}{R_i}\right)V_{in} = -\left(\frac{10k\Omega}{1k\Omega}\right)4V_{p-p} = \underline{-40V_{p-p}}$

{ will be clipped at +Vsat / -Vsat cuz more than the Vsat value.

Summing Amplifiers and Variations

- Variation of the inverting amplifier
- Has 2 or more inputs, and its output voltage is proportional to the -ve of the algebraic sum of it's Vin.
- Variations of the summing amplifier include the = • averaging amplifier, and
  • scaling amplifier.

Summing Amplifiers



- Since no current flows into the op-amp input terminals, I_1 and I_2 are fully diverted into the feedback resistor R_f.

$\therefore I_f = I_1 + I_2 = \frac{V_{IN1}}{R_1} + \frac{V_{IN2}}{R_2}$

$0 - V_{out} = I_f R_f$

$V_{out} = -I_f R_f$

$V_{out} = -\left(\frac{V_{IN1}}{R_1} + \frac{V_{IN2}}{R_2}\right)R_f$

$V_{out} = -\left(\frac{R_f}{R_1}V_{IN1} + \frac{R_f}{R_2}V_{IN2}\right)$

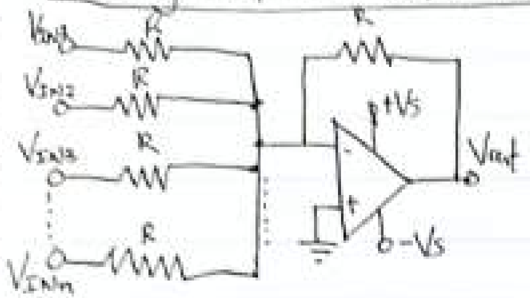
If with Unity Gain

If all the resistors all equal, $R_1 = R_2 = R_f$,

$V_{out} = -(V_{IN1} + V_{IN2})$

Inverting Amplifiers.

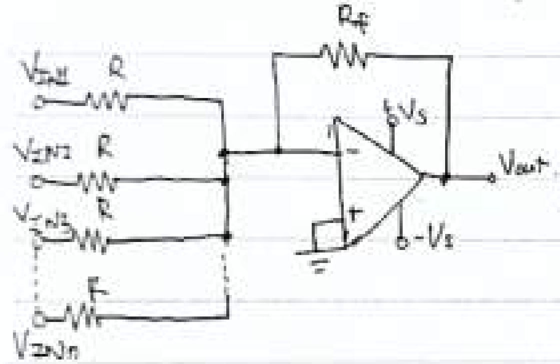
Summing Amplifier with "n" Identical Input Resistors



$$V_{out} = -(V_{IN1} + V_{IN2} + V_{IN3} + \dots + V_{INn})$$

Summing Amplifier with Gain Greater Than Unity

- When R_f > Input resistance R, the amplifier has a gain of R_f/R.

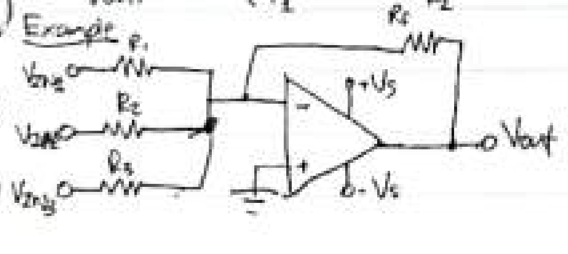


$$V_{out} = -\frac{R_f}{R}(V_{IN1} + V_{IN2} + V_{IN3} + \dots + V_{INn})$$

Multi-channel Scaling Amplifier

- By using different values of $R_1, R_2, R_3 \dots R_n$, the inputs of a summing amplifier can be subjected to different voltage gains.
- $V_{out} = -\left(\frac{R_f}{R_1}V_{IN1} + \frac{R_f}{R_2}V_{IN2} + \frac{R_f}{R_3}V_{IN3} + \dots + \frac{R_f}{R_n}V_{INn}\right)$

Example



~~$R_f = 2k\Omega$~~ $V_{IN1} = 1V$, $V_{IN2} = 2V$, $V_{IN3} = 3V$

$R_1 = 15k\Omega$, $R_2 = 15k\Omega$, $R_3 = 15k\Omega$, $R_f = 15k\Omega$

$$V_{out} = -\left(\frac{15}{15}(1) + \frac{15}{15}(2) + \frac{15}{15}(3)\right) = -6V$$

Only 2 → No V_{IN3} & R_3

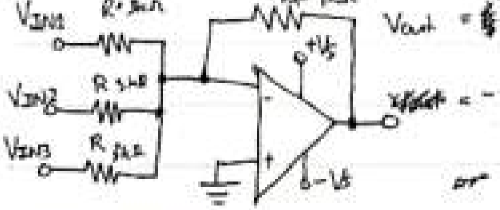
↳ $V_{IN1} = 0.2V$, $R_1 = 1k\Omega$, $R_f = 10k\Omega$

$V_{IN2} = 0.5V$, $R_2 = 1k\Omega$

$$V_{out} = -\left(\frac{10}{1}(0.2) + \frac{10}{1}(0.5)\right) = -7V$$

Averaging Amplifier

A summing amplifier can be made to produce the mathematical average of the input voltages by having $R/R_f = n$ (no. of input)



$$V_{out} = -\left(\tfrac{1}{3}V_{IN1} + \tfrac{1}{3}V_{IN2} + \tfrac{1}{3}V_{IN3}\right)$$

$$= -\tfrac{1}{3}(V_{IN1} + V_{IN2} + V_{IN3})$$

$$V_{out} = -\left(\frac{R_f}{R_1}V_{IN1} + \frac{R_f}{R_2}V_{IN2} + \frac{R_f}{R_3}V_{IN3} + \dots + \frac{R_f}{R_n}V_{INn}\right)$$

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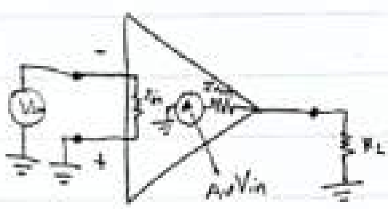
Comparators

Intro to comparators

- The open-loop voltage gain of an op-amp is extremely high. A very small voltage difference across the two input terminals will be able to saturate the output voltage to $\pm V_{sat}$.
- Whether the output voltage is $+V_{sat}$ or $-V_{sat}$ depends on which of the two input voltages is higher. An open-loop op-amp ~~used~~ uses for used for comparing two voltages is referred to as a comparator.
- Op-amps were originally designed for analog circuits. The ~~respons~~ response of an op-amp comparator is not very fast, so it is better to use a dedicated comparator IC for fast changing input signals. The internal circuit of a dedicated comparator is different from that of an op-amp.
- A dedicated comparator, such as LM311, or LM339, is designed to work with other digital devices. However this module mainly focuses on analog circuits. ~~Thus we will limit~~ ~~or~~

Op-Amp in the Open-Loop Configuration



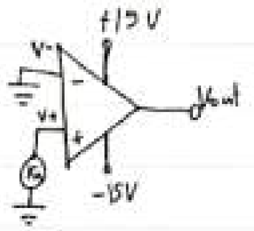
$A_v = A_{ol}$ = Open-Loop Voltage Gain.

$V_{out} = (V_+ - V_-) \times A_{ol}$

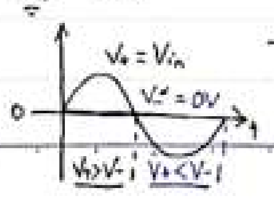
Op-Amp Comparators

3 Major type of Comparators: 1. Zero level comparator (or decoder), 2. Non-zero level comparator
3. Comparator with hysteresis.

Zero Level Comparators



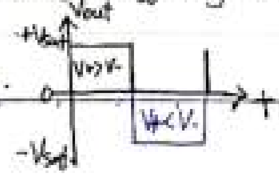
- Very small diff. in voltage between the 2 inputs drives the amplifier saturation.
- E.g. If $A_{ol} = 100{,}000$ & Voltage diff. between the 2 inputs $= 0.25mV$
  $V_{out} = (0.25mV)(100{,}000) = 25V$
- The amplifier will be driven to saturation.



- The output voltage of a comparator is determined by comparing the input voltages, V_+ and V_-:

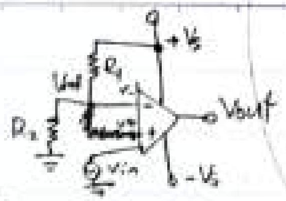
$V_+ > V_-$ causes $V_{out} = +V_{sat}$.

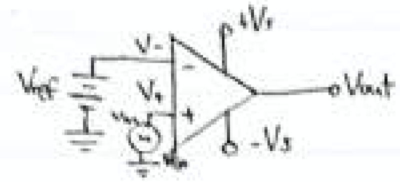
$V_+ < V_-$ causes $V_{out} = -V_{sat}$.



Comparators

Non-Zero Level Comparator



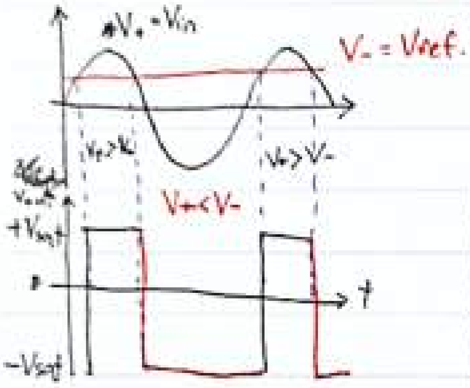


$\boxed{V_+ > V_- \Rightarrow V_{out} = +V_{sat}}$

$\boxed{V_+ < V_- \Rightarrow V_{out} = -V_{sat}}$

Vref ⇒ usually use a potential ~~meter~~ divider circuit.

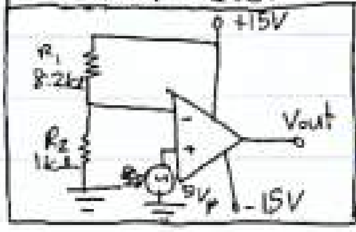
$V_{ref} = \left(\frac{R_2}{R_1+R_2}\right) \times V_s$



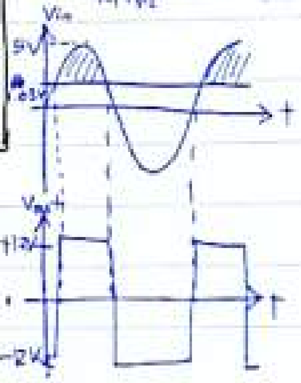
Example

5Vp sine wave inputted to a comparator. Sketch input & output wave. State amplitude & phase relationship

$\pm V_{sat} = \pm 12V$



Sol.
$V_{ref} = \frac{R_2}{R_1+R_2} \times V_s = \frac{1}{8.2+1} \times 15 = 1.63V$



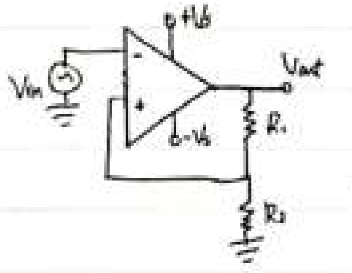
Hysteresis Comparator

Effects of Input ~~Mode~~ Noise on Comparator Operation

- In many practical situations, unwanted voltage fluctuation (noise) appears on the input line.
- The noise voltage becomes superimposed on the input voltage and can cause a comparator to erratically switch output states.

Reducing Noise Effect with Hysteresis

- To make the comparator less sensitive to noise applying positive feedback in an op-amp circuit known as hysteresis



- Hysteresis ⇒ higher ~~reference~~ reference level when Vout = +Vsat, and lower reference leven when Vout = -Vsat.
- The two refence voltages are ~~referred~~ ~~referred to~~ referred to as the upper trigger point (UTP) and the lower trigger point (LTP).

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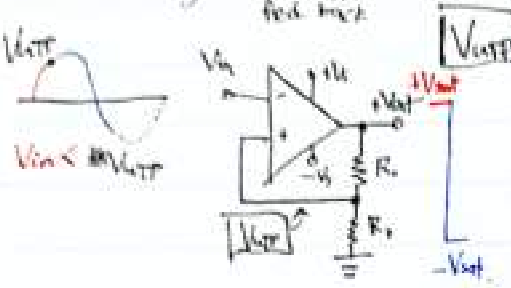
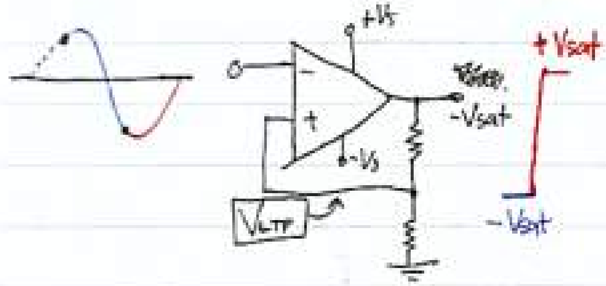
- Assuming that the output voltage is at it's positive maximum, $+V_{sat}$.
- The voltage ~~feedback~~ fed back to the non-inverting input is V_{UTP}. $\rightarrow V_{UTP} = \frac{R_2}{R_1 + R_2} \times V_{sat}$.



$\boxed{V_{UTP}}$ - Output at the maximum positive voltage.

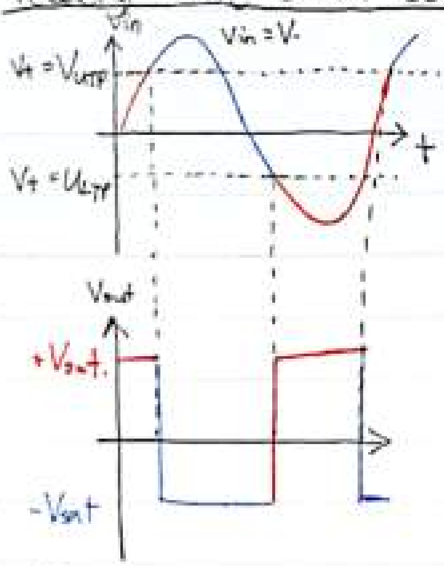
- Input exceeds V_{UTP}, output ~~switches~~ switches from the maximum positive voltage to the maximum negative voltage.

- When the input voltage exceeds V_{UTP}, the output voltage drops to it's negative maximum, $-V_{sat}$.
- The voltage fed back to the non-inverting input is V_{LTP}.



- Output at the maximum negative voltage.
- Input goes below V_{LTP}, output switches from the maximum negative voltage to the maximum positive voltage.

Reducing Noise Effect with hysteresis

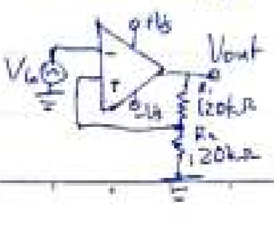


- To switch from the maximum negative voltage back to the maximum positive voltage, input voltage must now fall below V_{LTP}.
- Small amount of noise voltage therefore has no ~~effect~~ effect on the output.
- A comparator with hysteresis is also called a Schmitt trigger.
- The amount of hysteresis is defined by the difference of the 2 trigger levels.

$$\boxed{V_{HYS} = V_{UTP} - V_{LTP}}$$

Example

Find V_{LTP} & V_{UTP}, Assume that $\pm V_{sat} = 8V$



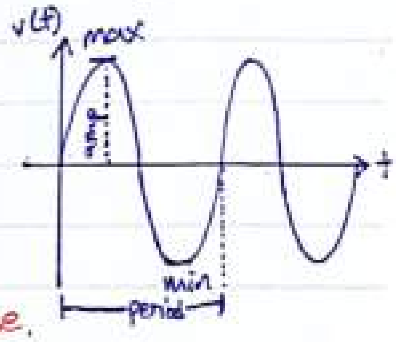
$V_{UTP} = \frac{R_2}{R_1 \times R_2} \times V_{sat} = 0.5 \times 8 = 4V$

$V_{LTP} = \frac{R_2}{R_1 \times R_2} \times -V_{sat} = 0.5 \times (-8) = -4V$

Phasors & Complex Numbers

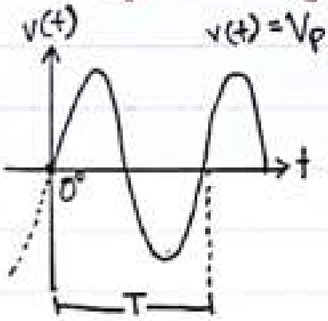
- When you throw a bowling ball, the ball is rotating at a constant angular velocity (angular speed in a specific direction).
- The angular movement at a point on the surface (circumference) of the ball is circular (relative to it's axis of rotation).

- When the movement against it's time, it shows a sinusoidal wave.
- Feature of a sinusoidal wave:
  - Angular velocity, — frequency, period
  - Direction of rotation,
  - Peak value. — amplitude

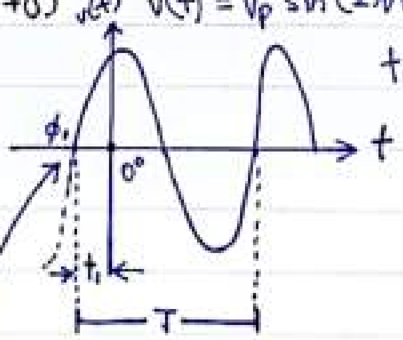


The direction of the rotation provides a reference to polarity of angle subtended at the center (or rotation axis) & so:
- A positive angle → rotation is counter-clockwise.
- A negative angle → rotation is clockwise.

$v(t) = V_p \sin(2\pi f t + 0)$



$v(t) = V_p \sin(2\pi f t + \phi_1)$



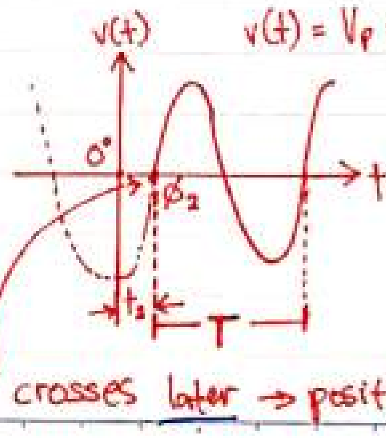
$t_1 = \frac{(\phi_1)}{2\pi} \times T$

- The angle ϕ_1 has a positive value.

A sine wave that

crosses earlier. → positive slope crosses zero level at ϕ_1

$v(t) = V_p \sin(2\pi f t + \phi_2)$



$t_2 = \frac{(\phi_2)}{2\pi} \times T$

- The angle ϕ_2 has a negative value.

crosses later → positive slope crosses zero level at ϕ_2

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AC voltage & AC current → sinusoidal.
↳ magnitude can be represented by either peak or rms values.

Calculating power by an AC supply. → all AC voltage & current are refered using the rms values.

~~Sing~~ Singapore → AC 230V → rms value of 230V

~~[illegible]~~ power adaptop → 100V - 240V ac → you can input rms 100V-240V rms to your adaptor.

Sinusoidal wave → has magnitude & an angular position / direction ← vector quantity

AC voltage & currents are called phasors.

A voltage phasor has the expression. → $\vec{V} = C \angle \phi$

phasor for voltage

magnitude in rms

phase angle in degrees.

- The magnitude C is always positive.
  → This is because only positive rms value are considered.
  → This is different from a vector that can show positive or negative magnitude.

- The phase angle ϕ can be zero, a positive or a negative value.
  ☆ The phase angle is only meaningful if there are 2 or more sine waves to be compared ~~[illegible]~~ with each other.

~~[illegible]~~

$v(t) = \underbrace{100}_{V_p} \sin(2\pi f t + \underbrace{30°}_{\phi})$ V

The magnitude $C = \frac{100}{\sqrt{2}} = 70.7$ V(rms)

$\frac{V_p}{\sqrt{2}}$

~~the phase angle [illegible]~~

The phase angle $\phi = 30°$

The phasor $\vec{V} = 70.7 \angle 30°$V

$i(t) = \underbrace{300}_{I_p} \sin(\underbrace{2000}_{\substack{2000mA \\ = 2A}}\pi t \underbrace{-60°}_{\phi})$ mA

The magnitude $C = \frac{300}{\sqrt{2}} = 212$ ~~[illegible]~~ mA (rms)

$\frac{I_p}{\sqrt{2}}$

The phase angle = -60°

The phasor $\vec{I} = 212 \angle -60°$mA

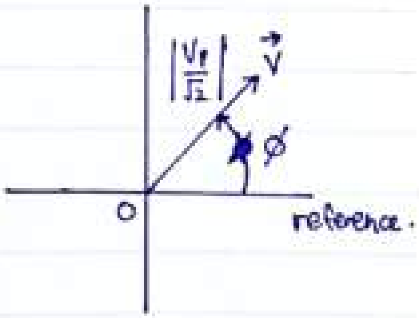
Phasors & Complex Numbers.

Sinusoidal expression is a function of time (i.e. in time domain).

$$v(t) = \underline{V_p} \sin(2\pi f t + \underline{\phi})\,V$$

The phasor $\rightarrow \vec{V} = \frac{V_p}{\sqrt{2}} \angle \phi\ V.$

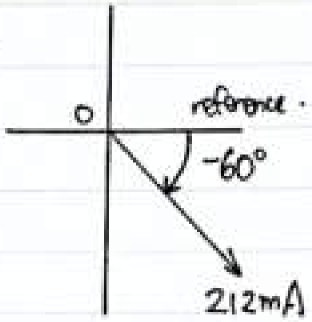
If the angle ϕ is positive.



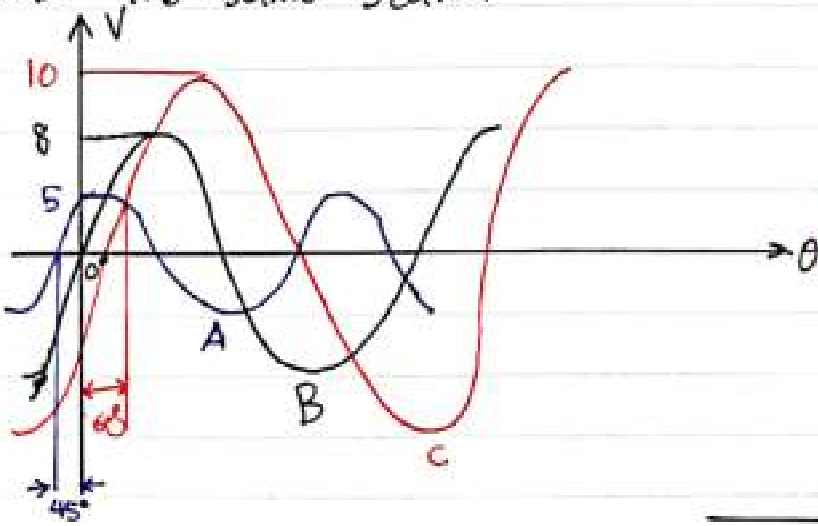
$i(t) = 300 \sin(2000\pi t - 60°)\,mA.$

The phasor $\vec{V} = 212 \angle -60\,mA.$

If the angle (ϕ) were to be positive.



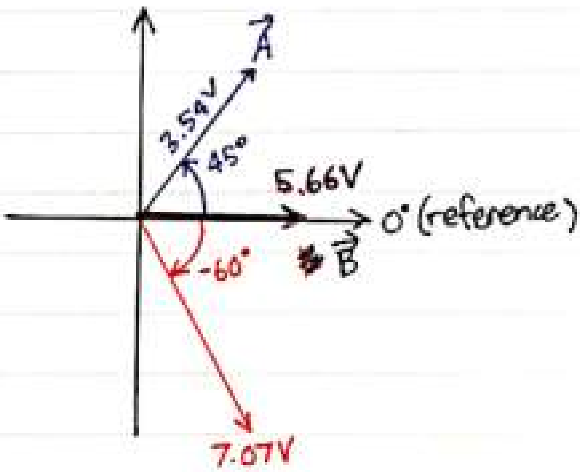
- When two or more sinusoidal functions are operating at the same frequency, their phasors can be sketched on the same phasor diagram.
- A phasor diagram may have a mix of phasors comprising voltages and currents.
- Voltages and currents have different units and don't therefore share the same scale.



$\vec{A} = \frac{5}{\sqrt{2}} \angle 45°V = 3.54\angle 45°V$

$\vec{B} = \frac{8}{\sqrt{2}} \angle 0°V = 5.66\angle 0°V$

$\vec{C} = \frac{10}{\sqrt{2}} \angle -60°V = 7.07\angle -60°V$



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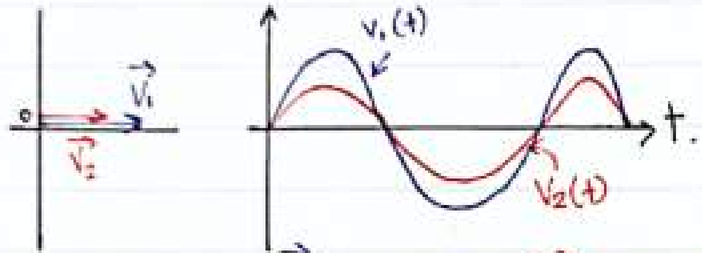
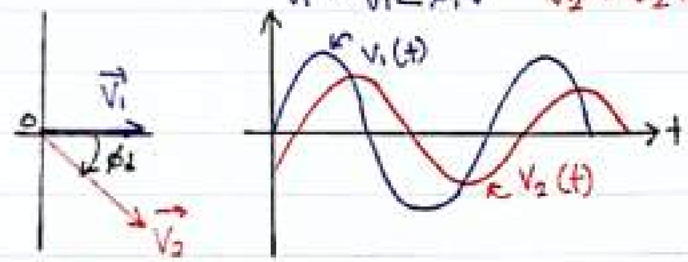
- If we are only representing one wave, we are usually not interested in whether it starts from the origin.
- However, if we are representing 2 or more waves, and they are not synchronized (out-of-phase), then their initial phase is important.



- Both wave are in phase.
- No phase difference.

$\phi_1 = \phi_2$

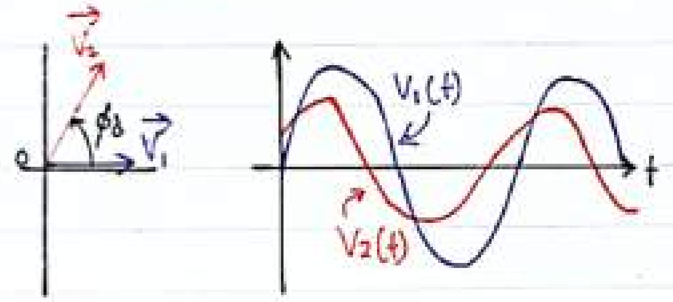
$\vec{V_1} = V_1 \angle \phi_1 V$ $\quad \vec{V_2} = V_2 \angle \phi_2 V$



- Both wave are out-of-phase.
- phase difference $\rightarrow \phi_d = |\phi_1 - \phi_2|$

$V_1(t)$ leads $V_2(t)$ by ϕ_d

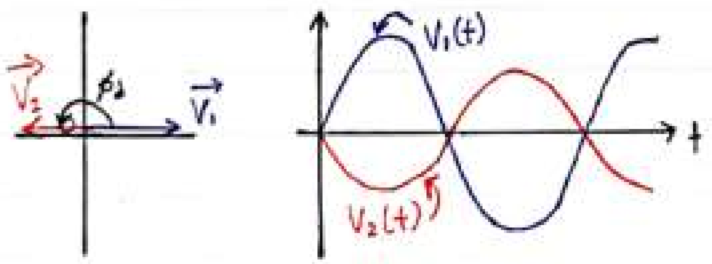
$V_2(t)$ lags $V_1(t)$ by ϕ_d



- Both wave are out-of-phase
- phase difference $\rightarrow \phi_d = |\phi_1 - \phi_2|$

$V_2(t)$ leads $V_1(t)$ by ϕ_d

$V_1(t)$ lags $V_1(t)$ by ϕ_d



- When 2 waves are 180° out-of-phase / inverted of each other.
- Phase difference $\rightarrow \phi_d = |\phi_1 - \phi_2|$
$= 180°$
- Inappropriate to state which ~~wave~~ wave is leading / lagging the other.

Phasors & Complex Numbers.

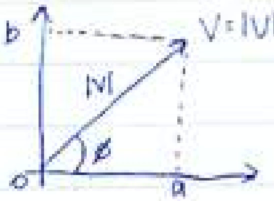
Addition

$V_1(t) = 20\sin(2000t - 30^\circ)V$, $V_2(t) = 10\sin(2000t + 45^\circ)V$

$V_1(t) + V_2(t) = ?$

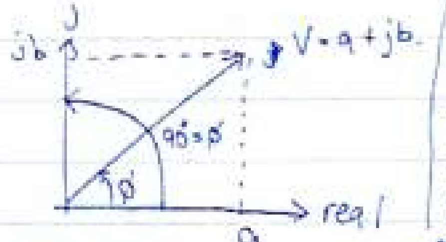
$V_1(t) : \vec{V_1} = \frac{20}{\sqrt{2}} \angle -30^\circ V = 14.14 \angle -30^\circ V$, $V_2(t) = \vec{V_2} = \frac{10}{\sqrt{2}} \angle 45^\circ V = 7.07 \angle 45^\circ V$

- At this juncture, we will learned about another form of phasor representation
- Trigonometrically, a phasor can be decomposed (broken down) into 2 components.
  - let phasor $\vec{V} = |V| \angle \phi$
    - Horizontal Component $a = |V| \cos\phi$
    - Vertical Component $b = |V| \sin\phi$



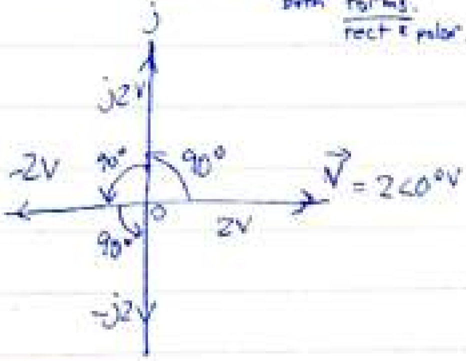
j Opperator.

- A phasor $\vec{V} = |V| \angle \phi$ is a complex number.
- To differentiate the vertical component from the horizontal, the j operator is used to represent the vertical axis
- Mathematically,
  - $j = \sqrt{-1}$, $j^2 = -1$, $\frac{1}{j} = -j$
- In phasor, j denotes an angle of 90° rotated counterclockwise from the horizontal axis.



The phasor diagram depicts both forms. rect & polar.

- To Illustrate the meaning of j operator, let phasor $\vec{V} = 2\angle 0^\circ V$ and is on the horizontal axis.
- Multiplying the magnitude 2 by j gives $j2V$ which is rotated 90° counterclockwise.
- A further 90° counterclockwise rotation gives $j^2(2)V$ or $-2V$.
- Another 90° counterclockwise of rotation gives $j^3(2)V$ or $-j2V$.

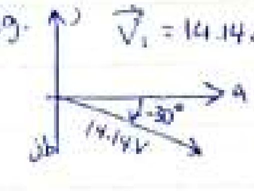


~~In General~~ $\vec{V} = a + jb$

- This is the rectangular form
- To convert from polar to rectangular.
  - $\rightarrow a = |V| \cos\phi$, $jb = j|V|\sin\phi$
- To convert from rectangular to polar

$|V| = \sqrt{a^2 + b^2}$, $\phi = \tan^{-1}\left(\frac{b}{a}\right)$

eg.



$\vec{V_1} = 14.14 \angle -30^\circ V$ find $a + jb$

$a = 14.14 \cos(-30)$
$= 12.25V$

$jb = j14.14 \sin(-30)$
$= -j7.07V$

$\therefore 12.25 - j7.07V$

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Addition

$\vec{V}_1 = a_1 + jb_1$ and $\vec{V}_2 = a_2 + jb_2$

$\vec{V}_1 + \vec{V}_2 = (a_1 + a_2) + j(b_1 + b_2)$

Using sine wave

$\vec{V}_1 = 14.14 \angle -30° \rightarrow v_1(t) = 20\sin(2000t - 30°)V$

$\vec{V}_2 = 7.07 \angle 45° \rightarrow v_2(t) = 10\sin(2000t + 45°)V$

$\vec{V}_{12} = 17.37 \angle -6.84° V$

$v_{12}(t) = \underset{V_P}{17.37\sqrt{2}} \sin(2000t - 6.84°)V$

$= 24.6 \sin(2000t - 6.84°)V$

~~Important~~ The frequency of a new waveform follows that of the ~~original~~ original functions it derived from (in this case the 2000t.

e.g. $\vec{V}_1 = 14.14 \angle -30°$ and $\vec{V}_2 = 7.07 \angle 45° V$.

$\vec{V}_1 + \vec{V}_2 = ?$

① convert to rectangular form →

$\vec{V}_1 = 12.25 - j7.07$ $\vec{V}_2 = 5 + j5V$.

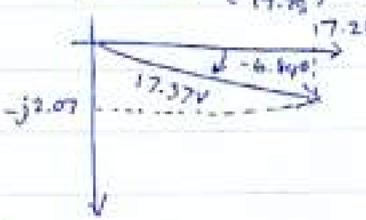
② adding:

$\vec{V}_1 + \vec{V}_2 = (12.25 + 5) + j(-7.07 + 5)V = 17.25 - j2.07V$

③ convert back to polar.

$|V| = \sqrt{17.25^2 + 2.07^2} = 17.37V$.

$\phi = \tan^{-1}\left(\frac{-2.07}{17.25}\right) = -6.84$ $\therefore 17.37 \angle -6.84°$



Substraction

$\vec{V}_1 - \vec{V}_2 = (a_1 - a_2) + j(b_1 - b_2)$

e.g. $\vec{V}_1 = 18 + j5V$, and $\vec{V}_2 = 6 - j3V$.

$\vec{V}_1 - \vec{V}_2 = (18 - 6) + j(5 - -3)$

$= 12 + j8V$

Multiplication

$\vec{V}_1 \times \vec{V}_2 = (a_1 + jb_1) \times (a_2 + jb_2)$

rect. $= (a_1 a_2 - b_1 b_2) + j(a_1 b_2 + a_2 b_1)$

$\vec{V}_1 \times \vec{V}_2 = (|V_1| \angle \phi_1) \times (|V_2| \angle \phi_2)$

polar $= (|V_1| \times |V_2|) \angle (\phi_1 + \phi_2)$

e.g. $\vec{V}_1 = 15 + j5V$ and $\vec{I}_1 = 6 + j3A$

$\vec{V}_1 \times \vec{I}_1 = ((15 \times 6) - (5 \times 3)) + j((5 \times 6) + (15 \times 3))VA$

$= 75 + j75VA$

$\vec{V}_1 = 15.81 \angle 18.43° V$, and $\vec{I}_1 = 6.7 \angle 26.57 A$

$\vec{V}_1 \times \vec{I}_1 = (15.81 \times 6.7) \angle (18.43° + 26.57°)VA$.

$= 106 \angle 45 VA$

Division

$\vec{V}_1 \div \vec{V}_2 = (|V_1| \angle \phi_1) \div (|V_2| \angle \phi_2)$

$= \left(\frac{|V_1|}{|V_2|}\right) \angle (\phi_1 - \phi_2)$

e.g. $\vec{V}_1 = 15.81 \angle 18.43° V$ and $\vec{I}_1 = 6.7 \angle 26.57° A$

$\frac{\vec{V}_1}{\vec{I}_1} = \frac{15.81}{6.7} \angle (18.43 - 26.57)$

$= 2.36 \angle -8.14° \Omega$

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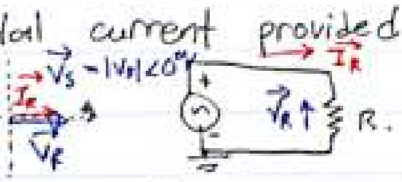
Capacitor

Resistive ac circuit

- A sinusoidal voltage always produces a sinusoidal current provided the signal is not distorted.
- Operated at same frequency



- Current and voltage waves are moving up and down simultaneously and crossing their respective zero level at the same instant.
- The current & voltage are said to be in phase.

→ ~~Let~~ To show, let $V_s(t) = V_p \sin(2\pi f t)V$

The current flowing → $i_R(t) = I_p \sin(2\pi f t)A$.

The voltage developed across the resistor → $v_R(t) = V_p \sin(2\pi f t)V$

$\therefore$ The ration $= \dfrac{V_R}{i_R} = \dfrac{V_R \sin(2\pi f t)V}{I_p \sin(2\pi f t)A} = \dfrac{V_p V}{I_p A} = \dfrac{|V_R|\sqrt{2}V}{|I_R|\sqrt{2}A} = \dfrac{|V_R|V}{|I_R|A}$ where $|V_R|$ & $|I_R|$ are rms

- From Ohm's law, the ratio gives resistance in ohm.
- Converting to phasor domain → $\dfrac{V_R}{I_R} = \dfrac{\vec{V_R}}{\vec{I_R}} = \dfrac{|V_R|}{|I_R|}\Omega$ //
- In a resistive ac circuit, the ratio is R → $\dfrac{\vec{V_R}}{\vec{I_R}} = \dfrac{|V_R|}{|I_R|}\Omega$.

Capacitive ac circuit

- A capacitance doesn't allow current to pass through it.
- In a dc circuit, its during the charging or the discharging process do we observe any current flow in the circuit.
- It is precisely the ever-changing voltage across the capacitor that generates the current in a capacitive ac circuit.
- It's the flow of charges that eventually accumulate on the plate surfaces of the capacitor during the charging process.
  - The discharging process reverses the polarity of the charges on the plates
- The alternations of charges on the capacitor constitute the current flow in the circuit
  - No current actually flow through the capacitor, regardless of dc. ac or dc.

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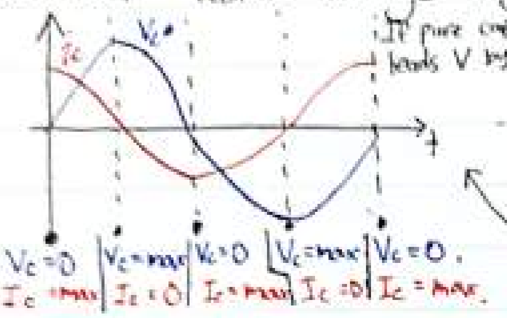
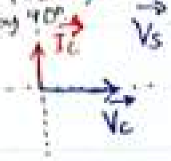
VI phase relationship in a capacitive ac circuit

- A capacitor behaves differently from a resistor in an ac circuit.
- Current leads voltage by 90° in a purely capacitive ac circuit.





$\vec{V_s} = |V_s| \angle 0° V$

the current is leading the voltage by 90°.

- In a capacitive ac circuit, current & voltage waves are sinusoidal that cross their zero level at different ~~stages~~ instants.
- ~~To understand this~~ Why? → $\underline{Q = CV}$ or $\underline{i_c(t)\Delta t = C\Delta V}$ where ΔV is change of V over time Δt.

→ Thus in ac, current $i_c(t) = C\frac{dv_c}{dt}$ A

- The supply voltage is $V_{s(t)}$ where $V_{s(t)} = V_p \sin(2\pi f t)$ V
- Sub in for $V_c(t)$ in the $i_c(t)$ ~~circuit~~ circuit → $i_c(t) = C\frac{d}{dt}V_p \sin(2\pi f t)$ A
- The current after differentiation is.

$$\left.\begin{aligned} i_c(t) &= (2\pi f t) V_p \cos(2\pi f t) A \\ i_c(t) &= (2\pi f t) V_p \sin(2\pi f t + 90°) A \end{aligned}\right\} \text{same.}$$

- Compared with a standard current expression.

$i_c(t) = I_p \sin(2\pi f t + \phi)$ A

→ $I_p = (2\pi f C)V_p$, Phase ange $\phi = 90°$

- The voltage across the capacitor is $v_c(t)$

$v_c(t) = V_p \sin(2\pi f t)$ V

- The ration of voltage to current.

$$\frac{V_c}{I_c} = \frac{V_p \sin(2\pi f t) V}{I_p \cos(2\pi f t) A} = \frac{V_p \sin(2\pi f t) V}{I_p \sin(2\pi f t + 90) A}$$

- Convert to phasor domain.

$$\frac{V_c}{I_c} = \frac{\vec{V_c}}{\vec{I_c}} = \frac{|V_c| \angle 0° V}{|I_c| \angle 90° A} = \frac{|V_c|}{|I_c|} \angle (0° - 90°) \Omega = \frac{|V_c|}{|I_c|} \angle -90° \Omega$$

use ohm's law.

$|V_c|$ & $|I_c|$ → rms value.

★ It's magnitude is called reactance X_c

$X_c = \frac{|V_c|}{|I_c|} \Omega$

★ It's impedance angle ϕ_c

$\phi_c = -90°$

★ → Mathematically, reactance X_c is expressed in terms of Capacitance C and operating freq, f

→ $\boxed{X_c = \frac{1}{2\pi f C} \Omega}$

★ The ratio ~~express~~ does express the opposition to current flow in an ac circuit

★ In a capacitive ac circuit, the ratio is termed as impedance $\vec{Z_c}$

$$\frac{\vec{V_c}}{\vec{I_c}} = \vec{Z_c} = \boxed{\frac{|V_c|}{|I_c|} \angle -90° \Omega}$$

Capacitor

e.g. ☆ Find the impedance of a 22nF capacitor connected to a 10V, 2000Hz V_s

Capacitance $C = 22nF = 22 \times 10^{-9} F$.

Reactance $X_C = \frac{1}{2\pi \times 2000 \times 22 \times 10^{-9}} \Omega = 3617 \Omega$

Impedance $\vec{Z_C} = 3617 \angle -90° \Omega$ (polar), or $-j3617$ (rect)

☆ Find the current flowing in ~~the~~ a 3.3mF capacitor connected to a 5V, 5kHz V_s

Capacitance $C = 3.3mF = 3.3 \times 10^{-6} F$.

Impedance $\vec{Z_C} = \frac{1}{2\pi \times 5000 \times 3.3 \times 10^{-6}} \angle -90° \Omega = 9.646 \angle -90° \Omega$

Current $= \frac{\vec{V_S}}{\vec{Z_S}} = \vec{I_C} = \frac{5 \angle 0° V}{9.646 \angle -90° \Omega} = 518 \angle 90° mA$ / $j518 mA$

☆ Find Capacitance when a current of 8mA is flowing connected to a 8V, 1.5kHz V_s.

Impedance $\vec{Z_C} = \frac{\vec{V_C}}{\vec{I_C}} = \frac{8 \angle 0° V}{8 \angle 90° mA} = 1 \angle -90° k\Omega$.

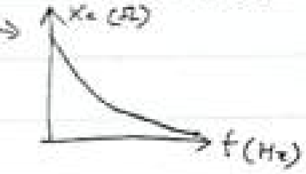
$8V = 8mA \times R$

Reactance $X_C = \frac{1}{2\pi \times 1.5 \times 10^3 \times C} \Omega = 1000 \Omega$.

$C = 106 nF$

Reactance against operating frequency

If $X_C = \frac{1}{2\pi f C} \Omega$ → Then for given C, X_C is inversely proportional to f. → $X_C \propto \frac{1}{f}$



- This charateristic curve for reactance has applications like
  - ☆ Filters → allows ac signals to pass through a circuit within a frequency range → called band pass or band stop.
  - ☆ HiFi sound fx → capacitor passes high frequency energy to tweeter
  - ☆ AC coupling → allows only ac signals to cross between circuits.

Resistor in an ac circuit

$\vec{Z} = \frac{V}{I} \angle 0° = R\Omega$.

→ $\vec{Z} = R\Omega$

Resistance in series $= R_T = R_1 + R_2 + R_3 + \ldots + R_n$.

When expressed in impedance $(\vec{Z_T}) = \vec{Z_T} = R_T = R_1 + R_2 + R_3 + \ldots + R_n$

If parallel $= \frac{1}{\vec{Z_T}} = \frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots \frac{1}{R_n}$

~~Capacitance in series $(C_T) = \frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots \frac{1}{C_n}$~~

use.

- Admittance (Y_T) for a parallel circuit $= \frac{1}{\vec{Z}_T}$, $\vec{Y}_1 = \frac{1}{\vec{R}_1}$, $\vec{Y}_2 = \frac{1}{\vec{R}_2}$, $Y_3 = \frac{1}{\vec{R}_3}$ ... $\vec{Y}_n = \frac{1}{\vec{R}_n}$

- Expressed in amittance $(\vec{Y}_T) = \vec{Y}_1 + \vec{Y}_2 + \dots + \vec{Y}_n$
- Likewise, in terms of conductance (G)

$\vec{Y}_T = G_T = G_1 + G_2 + \dots G_n$.

Admittance : $\vec{Y} = \frac{1}{V}\angle 0° = G\,S$ (Siemens)

Capacitor in series connections

$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots + \frac{1}{C_n}$ ← in both ac & dc.

By converting the capacitance to their impedance.

→ total Impedance value $= \vec{Z}_T$

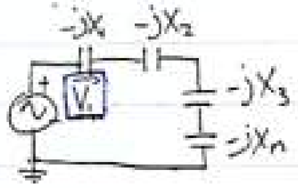
Apply KVL & Ohm's Law to the circuit.

$\vec{Z}_T = \frac{1}{\vec{I}_c}(\vec{V}_S) = \frac{1}{\vec{I}_c}(\vec{V}_1 + \vec{V}_2 + \vec{V}_3 + \dots + \vec{V}_n)$ $\boxed{\vec{V}_1 = \vec{V}_S \times \frac{\vec{Z}_1}{\vec{Z}_T}}$

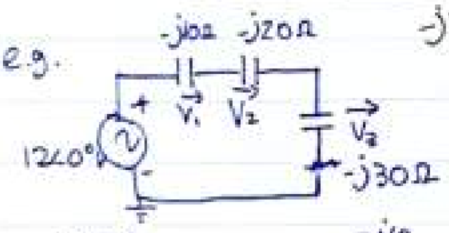
- $\vec{Z}_T = \frac{\vec{V}_S}{\vec{I}_c} = \left|\frac{V_S}{I_c}\right| \angle -90°\Omega = -jX_T\,\Omega$.

- Total impedance ($\vec{Z}_T$) in terms of series component

* $\vec{Z}_T = \underbrace{-jX_1 - jX_2 - jX_3 - \dots - jX_n}_{-jX_T}$.



e.g.



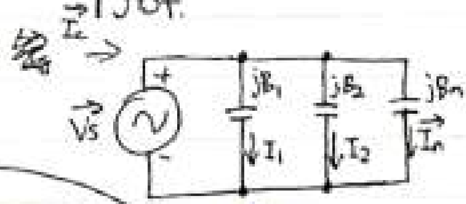
i) Find ($\vec{Z}_T$)

ii) Find $\vec{V}_1, \vec{V}_2, \vec{V}_3$

i) $\vec{Z}_T = -jX_T = -jX_1 - jX_2 - jX_3$
$= (-j10) + (-j20) + (-j30)$
$= -j60\Omega$

ii) $\vec{V}_1 = 12\angle 0° V \times \frac{-j10}{-j60} = 2\angle 0° V$
$\vec{V}_2 = 12\angle 0° V \times \frac{-j20}{-j60} = 4\angle 0° V$
$\vec{V}_3 = 12\angle 0° V \times \frac{-j30}{-j60} = 6\angle 0° V$

> Hence ($\vec{Y}_T$) in terms of ~~par~~ parallel
> $= \vec{Y}_T = \underbrace{jB_1 + jB_2 + \dots + jB_n}_{jB_T}$.

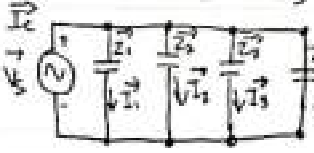


$\boxed{\vec{I}_1 = \vec{V}_S \times \vec{Y}_1}$

$Y_1 = \text{value} \angle 90°$

Capacitance in parallel connections.

$C_T = C_1 + C_2 + C_3 + \dots + C_n$



$\frac{1}{\vec{Z}_T} = \frac{1}{\vec{V}_S}(\vec{I}_c) = \frac{1}{\vec{V}_S}(\vec{I}_1 + \vec{I}_2 + \vec{I}_3 + \dots + \vec{I}_n)$

$\frac{1}{\vec{Z}_T} = \frac{1}{\vec{Z}_1} + \frac{1}{\vec{Z}_2} + \frac{1}{\vec{Z}_3} + \dots + \frac{1}{\vec{Z}_n}$

$\boxed{\frac{1}{\vec{Z}_T} = \vec{Y}_T}$ $\vec{Y}_T = \vec{Y}_1 + \vec{Y}_2 + \vec{Y}_3 + \dots + \vec{Y}_n$ | Ohm's Law → $\vec{Y}_T = \frac{\vec{I}_c}{\vec{V}_S} = \left|\frac{I_c}{V_S}\right| \angle 90°\Omega = jB_T\,S$.

B_T = total susceptance

Capacitors

Capacitors in parallel

e.g.

i) Find $\vec{Y}_T$

(ii) Find $\vec{I}_1$, $\vec{I}_2$, $\vec{I}_3$

i) $\vec{Y}_T = j50mS + j70mS + j30mS = j150mS$ //

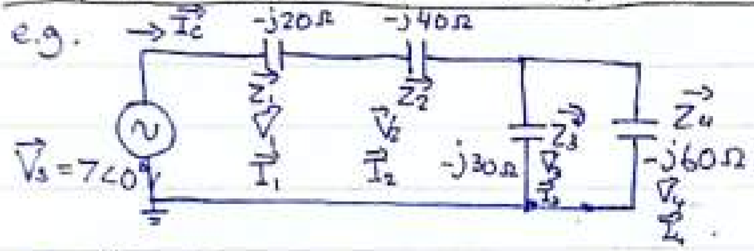
ii) $\vec{I}_1 = \vec{V}_s \times \vec{Y}_1 = 5\angle0° \times 150\angle90° mS = 750\angle90° mA$ //

$\vec{I}_2 = \vec{V}_s \times \vec{Y}_2 = 5\angle0° \times 70\angle90° mS = 350\angle90° mA$ //

$\vec{I}_3 = \vec{V}_s \times \vec{Y}_3 = 5\angle0° \times 30\angle90° mS = 150\angle90° mA$ //

V-I phase relationship in a capacitive ac circuit.

e.g.



i) Find ($\vec{Z}_T$)

ii) Find $\vec{I}_c$, $\vec{I}_1$, $\vec{I}_2$, $\vec{I}_3$, $\vec{I}_4$

iii) Find $\vec{V}_1$, $\vec{V}_2$, $\vec{V}_3$, $\vec{V}_4$

i) $\vec{Z}_1 + \vec{Z}_2 = -j20 + -j40 = -j60\,\Omega$

$\vec{Z}_3 + \vec{Z}_4 = \frac{1}{-j30} + \frac{1}{-j60} = \frac{1}{Z_{34}}$, $Z_{34} = -j20\,\Omega$

$\vec{Z}_T = -j60 + -j20 = -j80\,\Omega$ //

ii) $\vec{I}_c = \frac{\vec{V}_s}{\vec{Z}_T} = \frac{7\angle0° V}{-j80\,\Omega} = 0.0875\angle90° A = 8.75\angle90° mA$ //

$\vec{I}_1 = \vec{I}_2 = 8.75\angle90° mA$ //

$\vec{I}_3 = 8.75\angle90° \times \frac{-j60}{-j60 + -j30} = 58.33\angle90° mA$ //.

$\vec{I}_4 = 8.75\angle90° \times \frac{-j30}{-j30 + -j60} = 29.17\angle90° mA$ //.

$\boxed{I_c \times \frac{\vec{Z}_4}{\vec{Z}_4 + \vec{Z}_3}}$

iii) $\vec{V}_1 = V_s \times \frac{\vec{Z}_1}{\vec{Z}_T} = 7\angle0° \times \frac{-j20}{-j80} = 1.75\angle0° V$ //

$\vec{V}_2 = V_s \times \frac{\vec{Z}_2}{\vec{Z}_T} = 7\angle0° \times \frac{-j40}{-j80} = 3.5\angle0° V$ //

$\vec{V}_3 = \vec{V}_4 = V_s \times \frac{\vec{Z}_{34}}{\vec{Z}_T} = 7\angle0° \times \frac{-j20}{-j80} = 1.75\angle0° V$ //

No.

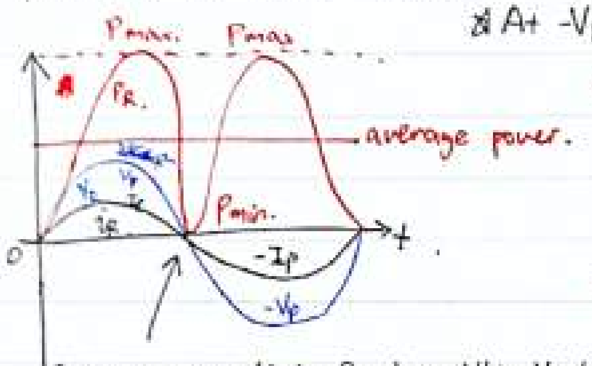
Date

Types of AC capacitive circuit:

1) Instantaneous power, 2) True Power, 3) Reactive Power.

1). Instantaneous power.

- In a resistive circuit, voltage (V_R) current (I_R) vary from zero to their respective ~~power~~ positive peaks (V_P and I_P) and negative peaks ($-V_P$ and $-I_P$). ☆ At V_P & I_P, power → P_{max}.
  ☆ At $-V_P$ & $-I_P$, power → P_{max}.



Instaneous power (P_0) =0, when either V_c / I_c =0

- A positive power value such as Pmax means the power is delivered from the supply and dissipated ~~the~~ in the resistor.
- Pmin = 0W means that power is dissipated in the resistor throughout the cycle except when voltage & current are at zero point.

- $P_{avg} = \frac{1}{T}\int_0^t V_R i_R \, dt = \frac{V_P I_P}{2} = \frac{V_P}{\sqrt{2}} \frac{I_P}{\sqrt{2}} = V_{rms} I_{rms}$. → $\boxed{(V_P \times I_P) = P_{max}}$
- $\boxed{P_{avg} = \frac{V_P I_P}{2} = \frac{P_{max}}{2} \ / \ V_{rms} \times I_{rms}}$

2) True power

- Pavg can also be called the real and true power.
- Symbol of Ptrue.
- Unit of W
- Only resistors and components that contain resistance dissipate real power.

Apparent Power.

- $V_{s(rms)} \times I_{s(rms)}$ = apparent power.
- Symbol $\boxed{S = V_s \times I_s}$
- Unit in volt-ampere or VA.

} when ac reciping power, it draws current.

Power factor.

- Apparent power → used to provide power in ac circuit.
- The useful power → true power.
- Power factor (pf) is defined as the ratio & true power (P) to apparent power (S) = $\boxed{pf \cancel{\$} = \frac{P}{S}}$ → no unit. → value of range $0 \leq pf \leq 1$.
- In a resistive ac circuit, pf = 1 → as the ~~entire power~~ entire apparent power is converted to true power (S = P), $\boxed{pf = \frac{P}{P} = 1}$

Capacitors

P_{avg} over a cycle $= \frac{1}{T}\int_0^T v_c i_c \, dt = 0W$.

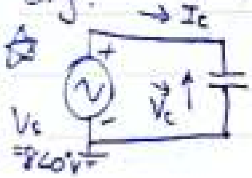
- During positive half of the cycle → power delivered to capacitor.
- During negative half of the cycle → same amount of power is returned to the source
- Hence the net power delivered to the capacitor over a cycle = 0.

5) <u>Reactive power.</u>

- The capacitor, like a resistor, still encounters the V & I in an ac circuit
- <u>Vrms × Irms</u> → power by the capacitor over a cycle.
- This is reactive power. → symbol Q (or P_r)
  → <u>unit is volt - ampere - reactive (VAR)</u>
  cannot use W as it's not true / real power.
- Indication of the power shifted to and fro between the ~~sauce~~ sources and the capacitor over a cycle.

∴ Reactive power in a capacitive ~~cycle~~ circuit → $\boxed{Q = V_{rms} I_{rms}}$

e.g.



☆ current = 8mA, Vs = 8V, 1.5kHz.
i) Find Pavg, ii) Reactive power.

i) $P_{avg} = 0W$ // ii) $Q = V_{rms} \times I_{rms} = 8V \times (8\times10^{-3})A = 64mVAR$ //

☆ Capacitor = 10Ω (reactance), Vs = 5V, 5kHz.
Find Reactive power.
$Q = V_{rms} I_{rms} = \frac{V_{rms}^2}{X_C} = \frac{5^2}{10} = 2.5VAR$ //

☆ Capacitor = 22nF, Vs = 10V, 2000Hz
i) Find true power ii) reactive power.
i) True power (P) = 0W //
ii) $X_C = \frac{1}{2\pi \times 2000 \times (22\times10^{-9})} = 3617\Omega$
$Q = V_{rms} I_{rms} = \frac{V_{rms}^2}{X_C} = \frac{10V^2}{3617\Omega} = 0.0276VAR = 27.6mVAR$ //

☆ In purely capacitive ac circuit, there is no ~~pow~~ dissipation of power
☆ pf $= \frac{0}{S} = 0$ → power factor. $\boxed{P = 0W}$
☆ The entire apparent power is converted to reactive power
$\boxed{S = Q}$

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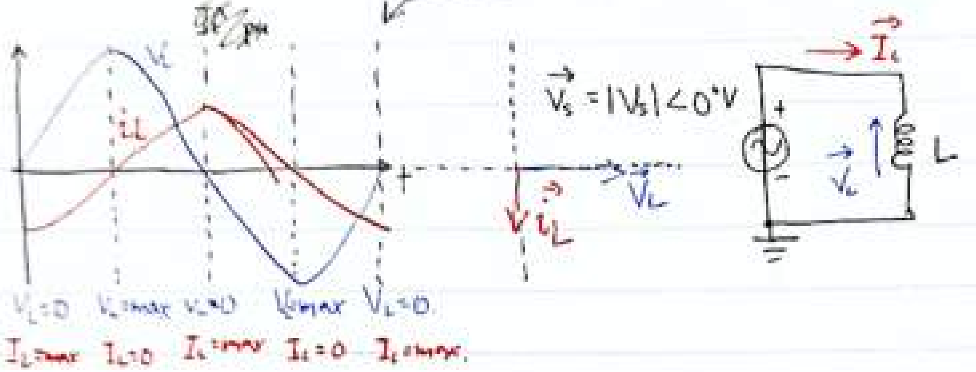
Date 15 . 2 . 22.

Inductors

- In a purely inductive circuit, $\vec{V_L}$ leads $\vec{I_L}$ by 90°
- $V_L = LI_P \cos(t)$
- Inductance impedance is given by: $\vec{Z_L} = X_L \angle 90° = jXL$
  where $X_L = 2\pi f L$



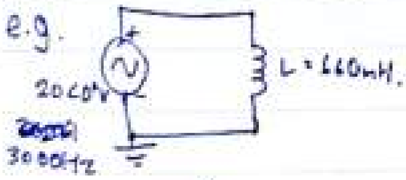
$i_L(t) = I_P \sin(2\pi f t + \phi) A \Rightarrow I_P = \left(\frac{1}{2\pi f L}\right) V_P \quad \phi = -90°$

$\frac{V_L}{i_L} = \frac{V_P \sin(2\pi f t) V}{I_P \sin(2\pi f t - 90°) A} \Rightarrow \frac{\vec{V_L}}{\vec{I_L}} = \frac{|V_L| \angle 0° V}{|I_L| \angle -90° A} = \frac{|V_L|}{|I_L|} \angle 90° \Omega = \vec{Z_L}$ $\quad |V_L|$ & $|I_L| \rightarrow$ rms.

- Though it's not a resistance, the ratio does express the opposition to current flow in an ac circuit. → the inductive ac circuit, the ratio is termed impedance, $\vec{Z_L}$.
- It's magnitude is ~~at the~~ the reactance $X_L \rightarrow \frac{|V_L|}{|I_L|} \Omega$; impedance angle $\phi_L = 90°$

$\boxed{\therefore X_L = 2\pi f L \ \Omega}$

e.g.

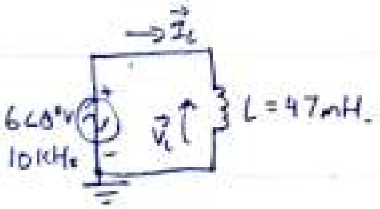


Find impedance?

$L = 660mH = 660 \times 10^{-3} H.$

Reactance $X_L = 2\pi \times 3000 \times 660 \times 10^{-3} \Omega = 4.15 \Omega$

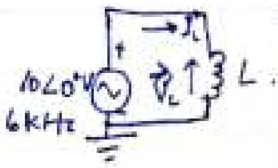
$\therefore$ Impedance $= 4.15 \angle 90° \Omega$ / $j4.15\Omega$



Find I_L?

$\vec{Z_L} = 2\pi \times 10000 \times 47 \times 10^{-3} \angle 90° \Omega$
$= 2953 \angle 90° \Omega$

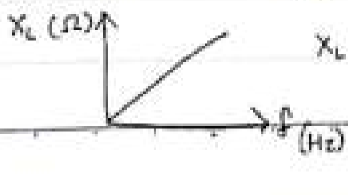
$\vec{I_L} = \frac{\vec{V_s}}{\vec{Z_L}} = \frac{6 \angle 0°}{2953 \angle 90°}$
$= 2.03 \angle -90° mA$
or $-j2.03 mA$



$I_L = 5mA$, Find L?

$\vec{Z_L} = \frac{\vec{V_s}}{\vec{I_L}} = \frac{10 \angle 0°}{5 \angle -90°} = 2 \angle 90° k\Omega$

$X_L = 2\pi \times 6 \times 10^{-3} \times L = 2k\Omega$ → $L = \frac{2 \times 10^3}{2\pi \times 6 \times 10^3} H$
$= 0.053H = 53mH$



$X_L = 2\pi f L (\Omega)$

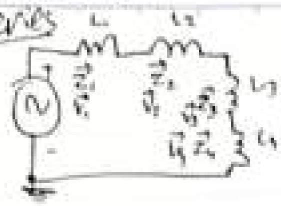
$X_L \propto f$.

~~Filter~~ Uses:
- Filter → to allow low freq ac sig. to pass through a circuit easily.
- Hi-Fi
- Magnetic coupling → provide electrical isolation of one circuit from another.
- Tranfo → pri & sec have diff gnd ~~paths~~ points.

No. PEEE-13.
Date 15.2.22.

Inductors

Series



$$\boxed{L_T = L_1 + L_2 + L_3 + L_4 + \ldots + L_n}$$

$$Z_T = \frac{1}{I_L}(\vec{V_S}) \quad (V_S = V_1 + V_2 + V_3 + \ldots + V_n)$$

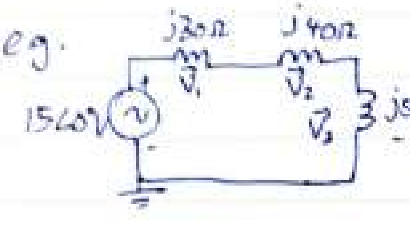
$$\boxed{Z_T = Z_1 + Z_2 + Z_3 + Z_4 + \ldots + Z_n}$$

$$\vec{Z_T} = \frac{\vec{V_S}}{\vec{I_L}} = \left|\frac{V_S}{I_L}\right| \angle 90^\circ \Omega \; \boxed{jX_T \, \Omega}$$

$$\to \vec{Z_T} = jX_1 + jX_2 + \ldots + jX_n$$

$= Z_1$, $= Z_2$, Z_n

e.g.



i) Find $\vec{Z_T}$
ii) Find $\vec{V_1}, \vec{V_2}, \vec{V_3}$

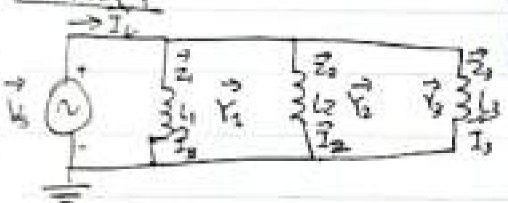
i) $\vec{Z_T} = j30 + j40 + j50$
$= j120\,\Omega$ //

ii) $\vec{V_1} = \vec{V_S} \times \frac{\vec{Z_1}}{\vec{Z_T}} = 15\angle 0^\circ \times \frac{j30}{j120} = 3.75\angle 0$

$\vec{V_2} = \vec{V_S} \times \frac{\vec{Z_2}}{\vec{Z_T}} = 15\angle 0^\circ \times \frac{j40}{j120} = 5\angle 0^\circ V$ //

$\vec{V_3} = \vec{V_S} \times \frac{\vec{Z_3}}{\vec{Z_T}} = 15\angle 0^\circ \times \frac{j50}{j120} = 6.25\angle 0$ //

Parallel



$$\boxed{\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots + \frac{1}{L_n}}$$

$$\frac{1}{Z_T} = \frac{1}{V_S}(\vec{I_L}) \quad (\vec{I_L} = I_1 + I_2 + I_3 + \ldots + I_n).$$

$$\boxed{\frac{1}{Z_T} = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} + \ldots + \frac{1}{Z_n}}$$

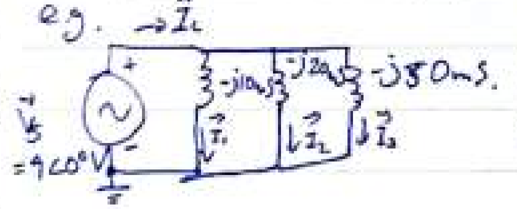
Admittance. $= \vec{Y_T} = \frac{1}{\vec{Z_T}}$ $\quad \boxed{\vec{Y_T} = \vec{Y_1} + \vec{Y_2} + \vec{Y_3} + \ldots + \vec{Y_n}}$

$$\vec{Y_T} = \frac{\vec{I_L}}{\vec{V_S}} = \left|\frac{I_L}{V_S}\right| \angle -90^\circ S = -jB_T S.$$

Susceptance $\to$ B.

Hence. $\vec{Y_T} = -jB_T = -jB_1 - jB_2 - jB_3 - \ldots - jB_n$

e.g.



Find i) $\vec{Y_T}$; ii) $\vec{I_1}, \vec{I_2}$ & $\vec{I_3}$

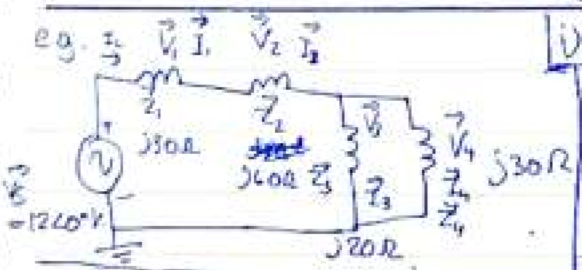
i) $\vec{Y_T} = -j10 - j20 - j50 = -j80\,mS$ //

ii) $\vec{I_1} = \vec{V_S} \times \vec{Y_1} = (9\angle 0^\circ V) \times (10\angle -90\,mS) = 90\angle -90\,mA$ //

$\vec{I_2} = \vec{V_S} \times \vec{Y_2} = (9\angle 0^\circ V) \times (20\angle -90\,mS) = 180\angle -90\,mA$ //

$\vec{I_3} = \vec{V_S} \times \vec{Y_3} = (9\angle 0^\circ V) \times (50\angle -90\,mS) = 450\angle -90\,mA$ //

e.g.



i) Find Z_T ii) $\vec{I_L}, \vec{I_1}, \vec{I_2}, \vec{I_3}, \vec{I_4}$ iii) $\vec{V_1}, \vec{V_2}, \vec{V_3}, \vec{V_4}$.

i) $Z_{12} = j30 + j60 = j90$.

$Y_{34} = \frac{1}{j20} + \frac{1}{j30} = -j0.08333$; $Z_{34} = \frac{1}{Y_{34}} = \frac{1}{-j0.0833} = j12\,\Omega$

$Z_T = j90 + j12 = j102\,\Omega$ //

ii) $\vec{I_L} = \frac{\vec{V_S}}{\vec{Z_T}} = \frac{12\angle 0 V}{j102\,\Omega} = 117.6\angle 90\,mA$.

$\vec{I_1} = \vec{I_2} = \vec{I_L} = 117.6\angle 90\,mA$ //

$\vec{I_3} = \vec{I_L} \times \frac{\vec{Z_4}}{\vec{Z_{34}}} = 117.6\angle 90 \times \frac{j30}{j20 + j30} = 70.6\angle 90^\circ mA$ //

$I_4 = \vec{I_T} - \vec{I_3} = 117.6\angle 90 - 70.6\angle 90^\circ = 47\angle 90^\circ mA$ //

iii) $\vec{V_1} = \vec{V_S} \times \frac{\vec{Z_1}}{\vec{Z_T}} = (12\angle 0) \times \frac{j30}{j102} = 3.53\angle 0^\circ V$ //

$\vec{V_2} = \vec{V_S} \times \frac{\vec{Z_2}}{\vec{Z_T}} = (12\angle 0) \times \frac{j60}{j102} = 7.06\angle 0^\circ V$ //

$\vec{V_3} = \vec{V_4} = \vec{V_S} \times \frac{\vec{Z_{34}}}{\vec{Z_T}} = (12\angle 0) \times \frac{j12}{j102}$

$= 1.41\angle 0^\circ V$ //

No. PEEE-15

Date 16.2.22

RC Circuits

$\vec{Z}_T = \vec{Z}_R + \vec{Z}_C$

$\therefore \boxed{\vec{Z}_T = R - jX_C}$

$\vec{Z}_T = |Z_T| \angle \phi$

$\boxed{|Z_T| = \sqrt{R^2 + X_C^2}}$

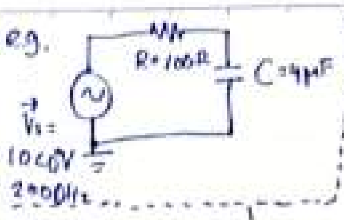
$\phi = \tan^{-1}\left(\frac{-X_C}{R}\right) = -\tan^{-1}\left(\frac{X_C}{R}\right)$

$\star\ \phi \rightarrow$ negative value

$0 \geq \phi \geq -90°$

$V_S = |V_S| \angle \phi V.$

e.g.



Find $\vec{Z}_T$?

Reactance $X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 1000 \times 4 \times 10^{-6}}$

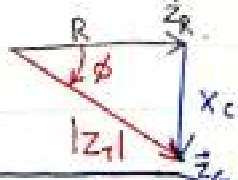
$= 20\Omega$

Capacitive Impedance $= \vec{Z}_C = -jX_C = -j20\Omega$

$\vec{Z}_T = R + \vec{Z}_C = 100 - j20\Omega$

$\vec{Z}_R = R \angle 0° \Omega$; $\vec{Z}_C = X_C \angle -90° \Omega$

$\hookrightarrow \vec{Z}_T = \sqrt{R^2 + X_C^2} \angle \phi\ \Omega.$



$R = |Z_T| \cos\phi$

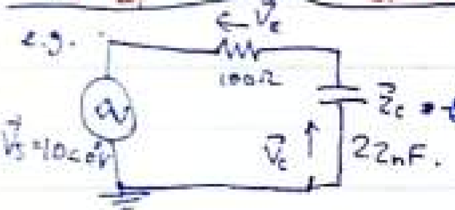
$X_C = |Z_T| \sin\phi$

$\vec{V}_R = \frac{R}{\vec{Z}_T} \vec{V}_S$; $\vec{V}_C = \frac{\vec{Z}_C}{\vec{Z}_T} \vec{V}_S$

e.g.

$Z_T = 102 \angle -11.3° \Omega$

e.g.



Determine V_C a) $f = 1kHz$ b) $= 500kHz$.

a) $X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 1000 \times 22 \times 10^{-9}}$

$= 7234\Omega$.

$\vec{Z}_T = (100 - j7234)\Omega$.

VDR $\rightarrow V_C = \frac{X_C}{|Z_T|} V_S$

$= \frac{7234}{\sqrt{100^2 + 7234^2}} (10V)$

$V_C \approx 10V = V_S$.

b) $X_C = \frac{1}{2\pi \times 500 \times 10^3 \times 22 \times 10^{-9}}$

$= 14.5\Omega$.

$\vec{Z}_T = (100 - j14.5)\Omega$.

$V_C = \frac{X_C}{|Z_T|} = \frac{14.5}{\sqrt{100^2 + 14.5^2}} \times (10V)$

$V_C \approx 1.43V$ or 14.3% of V_S.

$\vec{I} = |I| \angle 0° A.$

$\vec{V}_R = |V_R| \angle 0° V.$

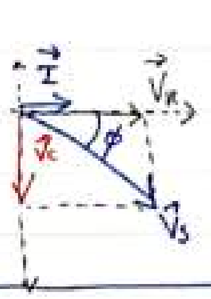
$\vec{Z}_C, \vec{V}_C = |V_C| \angle -90° V$

} The phasors.

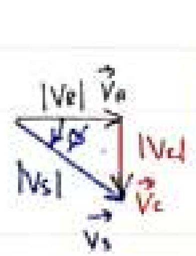
$\vec{V}_S = |V_S| \angle \phi V$ } Source voltage.

$|V_S| = \sqrt{|V_R|^2 + |V_C|^2}$

$\phi = -\tan^{-1}\left(\frac{X_C}{R}\right)$



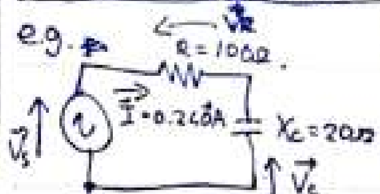
$\Rightarrow$



$|V_R| = |V_S| \cos\phi$

$|V_C| = |V_S| \sin\phi$

e.g.



$\vec{V}_R = I \times R = (0.2 \angle 0° A)(100)$

$= 20 \angle 0° V$

$\vec{V}_C = \vec{I} \cdot (X_C \angle -90)$

$= (0.2 \angle 0° A)(20 \angle -90° \Omega)$

$= 4(0° \angle 90°) = 4 \angle -90° V$

$\vec{V}_S = |V_S| \angle \phi V$

$|V_S| = \sqrt{|V_R|^2 + |V_C|^2} = \sqrt{20^2 + 4^2}$

$= 20.4V$

$\phi = -\tan^{-1}\left(\frac{4}{20}\right) = -11.3°$

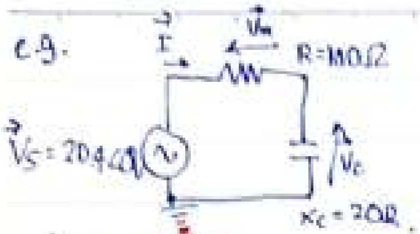
$\therefore \vec{V}_S = 20.4 \angle -11.3° V$

Impt → $(X_C \angle -90°)$ ← $\vec{V}_C = \vec{I}(\vec{X}_C \angle -90°)$

→ Series RC has a leading pf.

RC circuit

e.g.



Find $\vec{I}, \vec{V}_R, \vec{V}_C$ & sketch the phasor diagram (with V_S)

$\vec{Z}_T = |Z_T|\angle\phi\,\Omega$; $\vec{Z}_T = \sqrt{|R|^2 + |X_C|^2} = \sqrt{100^2 + 20^2} = 102\,\Omega$

$\phi = -\tan^{-1}\left(\frac{X_C}{R}\right) = -\tan^{-1}\left(\frac{20}{100}\right) = -11.3°$ ∴ $\vec{Z}_T = 102\angle -11.3°\,\Omega$.

$\vec{I} = \frac{\vec{V}_S}{\vec{Z}_T} = \frac{20.4}{102}\angle 0-(-11.3) = 0.2\angle 11.3°A$ //

$\vec{V}_R = \vec{I} \times R = (0.2\angle 11.3°A) \times (100\,\Omega) = 20\angle 11.3°V$ //

$\vec{V}_C = \vec{I} \times (X_C \angle -90°) = (0.2\angle 11.3°A) \times (20\angle -90°) = 4\angle 78.7°$ //

3 types of power : 1. Apparent power → $S = |I| \times |V_S|$ → unit VA

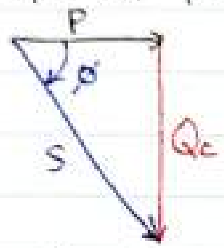
$= I^2|Z_T|$

2. Reactive power → $Q_C = |I|^2 \times X_C$ → unit VAR.

volt-ampere reactive

3. Real power → $P = I^2R$ → unit Watt.

↳ it is also the avg power over a cycle



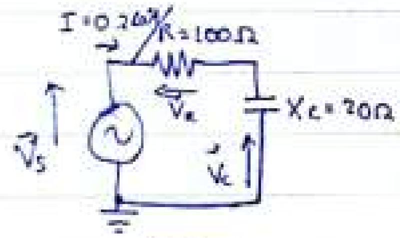
$$\boxed{P = S\cos\phi \quad Q_C = S\sin\phi \quad S = \sqrt{P^2 + Q_C^2}}$$

$pf = \frac{P}{S} = \frac{S\cos\phi}{S} = \cos\phi$ → no unit → it is leading.

$= \frac{P}{|Z_T|}$

$$\boxed{\phi = -\tan^{-1}\left(\frac{Q_C}{P}\right)}$$

e.g.



Sketch the power triangle and find pf.

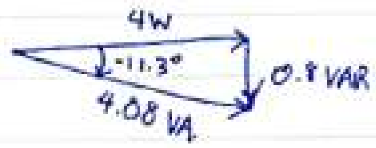
$P = I^2R = 0.2^2 \times 100 = 4W$ //

$Q_C = I^2 X_C = 0.2^2 \times 20 = 0.8VAR$ //

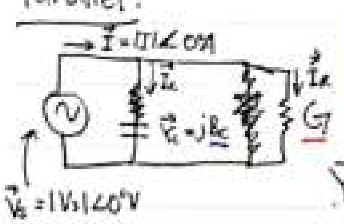
$S = I^2|Z_T| = (0.2^2)(\sqrt{100^2 + 20^2}) = 4.08VA$ //

$\phi = -\tan^{-1}\left(\frac{Q_C}{P}\right) = -\tan^{-1}\left(\frac{0.8}{4}\right) = -11.3°$

$pf = \cos(-11.3°) = 0.981$ (leading)



Parallel.



Susceptance $B_C = \frac{1}{X_C}$ → unit is SIEMEN. → ℧ / S.

Conductance $G = \frac{1}{R}$ → unit is SIEMEN

$\vec{Y}_T = G + \vec{Y}_C$

Admittance of R → $\vec{Y}_R = G\angle 0°S$

Admittance of C → $\vec{Y}_C = B_C\angle 90°S$

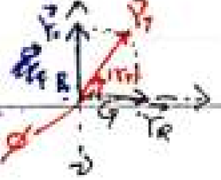
Total admittance → $\vec{Y}_T = \sqrt{G^2 + B_C^2}\angle\phi$ S.

$\vec{Y}_T = |Y_T|\angle\phi$ ← positive value $0° \leq \phi \leq 90°$

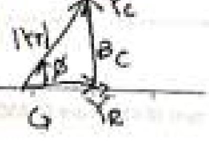
$\sqrt{G^2 + B_C^2}$; $\tan^{-1}\left(\frac{B_C}{G}\right)$

$$\boxed{\vec{I}_C = \vec{Y}_C\vec{V}_S}$$

jB_C



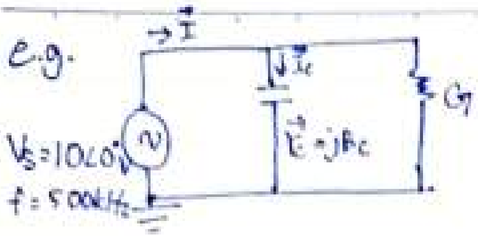
$$\boxed{G = |Y_T|\cos\phi \quad B_C = |Y_T|\sin\phi}$$



No.

Date

e.g.



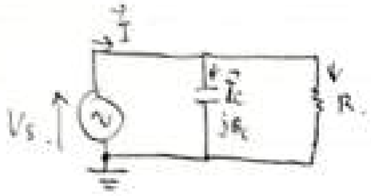
$R = 100\,\Omega$, $C = 22nF$, find $\vec{I}_C$

$B_C = 2\pi f C = 2\pi(500{,}000) \times (22 \times 10^{-9} S)$

$= 69.1 mS$.

~~$\vec{Y}_T = G(100 + j69.1)$ mS~~.

$\vec{I}_c = \vec{Y}_c \vec{V}_s = (j69.1 mS) \times (10\angle 0° V) = 691\angle 90° mA$ //



$\vec{V}_S = |V_S|\angle 0° V$

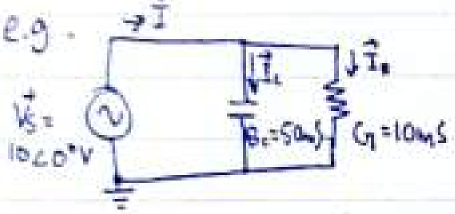
$\vec{I} = |I|\angle 0° A$.

$$\boxed{\begin{aligned}\vec{I}_R\ /G &= |I_R|\angle 0° A \\ \vec{I}_c\ /jB_C &= |I_c|\angle 90° A\end{aligned}}$$

$$\boxed{\begin{aligned}|I| &= \sqrt{|I_R|^2 + |I_c|^2} \\ \phi &= \tan^{-1}\left(\frac{|I_c|}{|I_R|}\right) = \tan^{-1}\left(\frac{B_c}{G}\right)\end{aligned}}$$

$$\boxed{\begin{aligned}|I_R| &= |I|\cos\phi \\ |I_c| &= |I|\sin\phi\end{aligned}}$$

e.g.



Find $\vec{I}_R$, $\vec{I}_C$ & $\vec{I}_T$

$\vec{I}_R = \vec{V}_S \times G = (10\angle 0°) \times (10) = 100\angle 0° mA$ //.

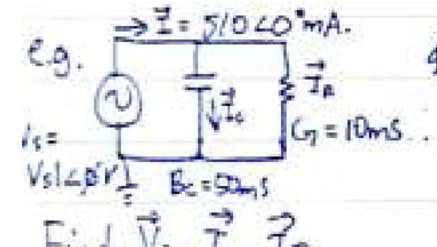
$\vec{I}_C = \vec{V}_S \times (B_c\angle 90°) = (10\angle 0°) \times (50\angle 90° mS) = 500\angle 90° mA$ //

$|\vec{I}| = \sqrt{|I_R|^2 + |I_c|^2} = \sqrt{100^2 + 500^2} = 510 mA$.

$\phi = \tan^{-1}\left(\frac{I_c}{I_R}\right) = \tan^{-1}\left(\frac{500}{100}\right) = 78.7°$

$\therefore \vec{I} = 510\angle 78.7 mA$ //

e.g.



Find $\vec{V}_S$, $\vec{I}_c$, $\vec{I}_R$

$\vec{Y}_T = |Y_T|\angle\phi\ S$.

$|Y_T| = \sqrt{|G|^2 + |B_c|^2} = \sqrt{10^2 + 50^2}\ mS = 51 mS$. $\therefore \vec{Y}_T = 51\angle 78.7° mS$

$\phi = \tan^{-1}\left(\frac{B_c}{G}\right) = \tan^{-1}\left(\frac{50}{10}\right) = 78.7°$

$\vec{V}_S = \frac{\vec{I}}{\vec{Y}_T} = \frac{510}{51}\angle(0° - 78.7°) V = 10\angle -78.7 V$ //.

$\vec{I}_R = \vec{V}_R \times G = (10\angle -78.7) \times (10) = 100\angle -78.7 mA$ //

$\vec{I}_c = \vec{V}_c \times (B_c\angle 90°) = (10\angle -78.7) \times (50\angle 90° mS)$

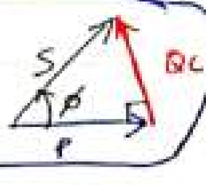
$= 500\angle 11.3 mA$ //

also absorbed in circuit.

In parallel → real power is dissipated as heat in Resistor.

→ real power also known as active power / true power.

$$\boxed{\underline{P = S\cos\phi} \quad \underline{Q_C = S\sin\phi} \qquad \underline{S = \sqrt{P^2 + Q_C^2}}}$$



$$\boxed{\begin{array}{l|l} S = V_S^2|Y_T| & I = V_S|Y_T| \\ P = V_S^2 R & I_C = V_S B_C \\ Q_C = V_S^2 B_C & I_R = V_S G \end{array}}$$

$R \to G$.

$|Y_T| = \sqrt{G^2 + B_C^2}$

$pf = \frac{P}{S} = \frac{G}{Y_T} = \frac{S\cos\phi}{S} = \cos\phi$

No. PEEE - 16.
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RL Circuit

series

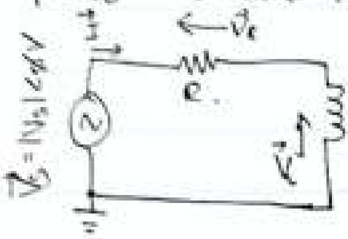
$\vec{Z}_T = R + jX_L$
$R + jX_L \angle 90°$ ← R→G (G if parallel)
$pf = \frac{P}{S} = \frac{R}{|Z_T|} = \cos\phi$

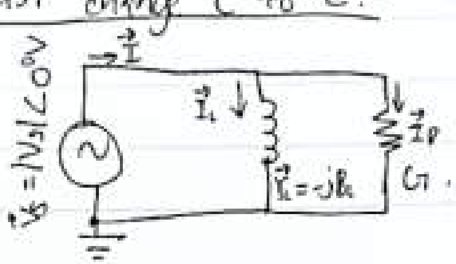
power factor is always lagging. ← since I is lagging V_s by ϕ

parallel

$\vec{Y}_T = G - jB_L$
$= G - B_L \angle -90°$.

power → same like RC. ← just change C to L ← X_C become X_L.



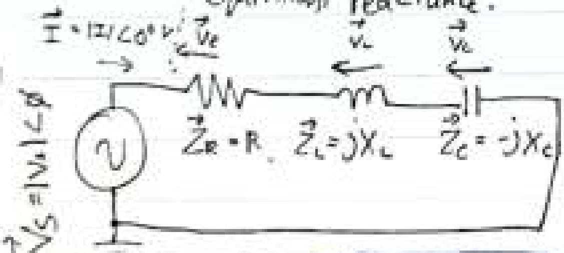


RLC Circuit

Series:

$\vec{Z}_T = R + (X_L \angle 90°) - (X_C \angle 90°)$
$= R + jX_L - jX_C$.
$= R + j\underbrace{(X_L - X_C)}_{= X = X_L - X_C}$

equivalent reactance.



$\vec{Z}_T = |Z_T| \angle \phi$
$|Z_T| = \sqrt{R^2 + (X_L - X_C)^2}$
$\phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right)$ ← $\boxed{X \leftrightarrow V}$

$X_L > X_C \to \phi$ +ve ← lagging
$X_L < X_C \to \phi$ -ve ← leading

↑ find pf

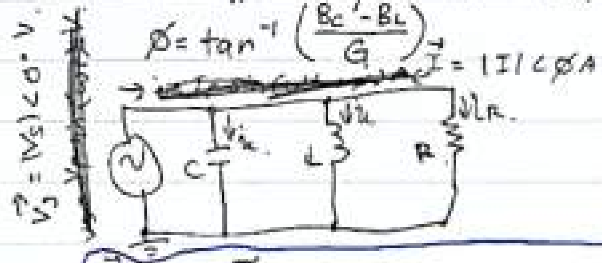
$\vec{Z}_R = R \angle 0° \Omega$.
$\vec{Z}_L = X_L \angle 90° \Omega$
$\vec{Z}_C = X_C \angle -90° \Omega$

$Q_L > Q_C \to S = \sqrt{P^2 + (Q_L - Q_C)^2}$
$P = S\cos\phi$
$Q = S\sin\phi$

equivalent susceptance.
↓
$B = B_C - B_L$.

parallel

$\vec{Y}_T = G - jB_L + jB_C$.
$\vec{Z}_T = \frac{1}{\vec{Y}_T} = \frac{1}{Y_T \angle \phi} = \vec{Z}_T \angle -\phi°$
$\phi = \tan^{-1}\left(\frac{B_C - B_L}{G}\right)$



$\vec{Y}_T = |Y_T| \angle \phi$
$|Y_T| = \sqrt{G^2 + (B_C - B_L)^2}$
$\phi = \tan^{-1}\left(\frac{B_C - B_L}{G}\right)$ ← $\boxed{B \leftrightarrow I}$

$B_C > B_L \to \phi$ +ve ← leading
$B_C < B_L \to \phi$ -ve ← lagging

$\vec{Y}_R = G \angle 0° S$
$\vec{Y}_L = B_L \angle -90° S$
$\vec{Y}_C = B_C \angle 90° S$

$S = \sqrt{P^2 + (Q_C - Q_L)^2}$
$P = S\cos\phi$
$Q_L = S\sin\phi$

$Q_L < Q_C \to S = \sqrt{P^2 + (Q_C - Q_L)^2}$
$P = S\cos\phi$
$Q = S\sin\phi$
(C−L) when C > L.
(L−C) when L > C.

Power → same as RC & RL ← just change C or L to (C−L) or (L−C)