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| **Formula** | **Explanation** |
| Basics of transistors |  |
| NPN and PNP transistors |  |
| BJT basics | It is a 3 terminal semiconductor device which can act as a insulator or conductor based on the applied input signal  Due to this property, it can be used as a switch in digital electronics and as an amplifier in the analog electronics  Bipolar indicates that both holes and electrons contribute in the flow of current    There are basically two types of BJT based on doping   1. NPN 2. PNP  |  |  | | --- | --- | | **NPN BJT**      Arrow indicates flow of current in the active region of operation | **PNP BJT**      Arrow indicates flow of current in the active region of operation | | **Working of BJT in various regions**  Depending on the biasing BJT has 4 regions of operation   * Active region [**used for Amplification**] * Cutoff region [**used for switching**] * Saturation region [**used for switching**] * Reverse active region – here gain provided by BJT is very less – so operation is this region is avoided  1. **Active region**  |  |  | | --- | --- | | **For NPN transistor**    To forward bias base-emitter junction :  To reverse bias base-collector junction :  So, in a nutshell : | **For PNP transistor**    To forward bias base-emitter junction :  To reverse bias base-collector junction :  So, in a nutshell : |  1. **cutoff region**  |  |  | | --- | --- | | **For NPN transistor**    To reverse bias base-emitter junction :  To reverse bias base-collector junction :  So, in a nutshell : | **For PNP transistor**    To reverse bias base-emitter junction :  To reverse bias base-collector junction :  So, in a nutshell : |  1. **saturation region**  |  |  | | --- | --- | | **For NPN transistor**    To forward bias base-emitter junction :  To forward bias base-collector junction :  So, in a nutshell : | **For PNP transistor**    To forward bias base-emitter junction :  To forward bias base-collector junction :  So, in a nutshell : |  1. **Reverse active region**  |  |  | | --- | --- | | **For NPN transistor**    To reverse bias base-emitter junction :  To forward bias base-collector junction :  So, in a nutshell : | **For PNP transistor**    To reverse bias base-emitter junction :  To forward bias base-collector junction :  So, in a nutshell : | | |   **🧼 Washing Machine = Transistor**   | **Step** | **Real-World Action (Washing Machine)** | **Transistor Equivalent** | | --- | --- | --- | | 🔌 **1. Plug in & switch ON** | Apply **DC voltage** — this is **biasing** |  | | 🔄 **2. Select washing mode (quick/delicate/etc.)** | Choose **configuration** (CE, CC, CB) |  | | 👕 **3. Add clothes** | Apply **input signal (AC)** |  | | 🌀 **4. Wash cycle processes clothes** | Transistor **amplifies or buffers** the signal |  | | ✅ **5. Get clean clothes** | **Output signal** — amplified, current boosted etc. |  |   **✅ What this analogy teaches perfectly:**   * **The machine needs power first** → Just like a transistor needs DC biasing to even function * **The mode defines how it works** → Just like configuration affects behavior (gain, impedance) * **The actual clothes are your signal** → Without a signal, the machine is powered but does nothing meaningful * **The result (clean clothes) is your output** → Just like the amplified or buffered signal at the output   **Various Configs of BJT**  The most common application of BJT is an amplifier.    Whenever we want to use it as an Amplifier there are various connection config we can do (in each config – one terminal of BJT is common in both input and output side)   1. Common Base config 2. Common Emitter config 3. Common Collector config  |  | | --- | | **Common Base config**  Here base terminal is common between input and the output side (here we have taken example of a NPN BJT)    Note : whenever we want to use it any config as amplifier – we must use it In the active region       * The direction of current for NPN and PNP will look like this     In common base config – behaviour of ckt can be described by two characteristics (these characteristics gives the overview of parameters when current and voltage changes)   1. Input characteristics 2. Output characteristics   **Input characteristics**  Input characteristics describes the relation between and (input parameters)) (VI characteristics) – for the fix value of  Note : we will discuss about NPN transistor    Here, when we increase Vcb voltage (c-b junction becomes more reverse bias) the curve becomes more steeper (that is due to thickening of depletion region and thinning of base region) – which in turn means less volt is required to forward bias the Emitter – base junction (thus increasing )   * Input impedance (this shows a little change in Vbe could result in large change in current ) (also this makes input impedance very low) * Thus, we can say in common base config the input impedance of Base emitter junction is very low (in Ohms)   **Output characteristics**  output characteristics describes the relation between and (output parameters)) (VI characteristics) – for the fix value of  Note : we will discuss about NPN transistor     * this shows if we increase , also increases * In this curve there are 3 regions   + - Active region     - Cutoff region     - Saturation region     **Active region**   * Here in the Active region , if we increase collector to base voltage () – current ( ) remains constant * In this region the relation between collector current and Emitter current can be given by     = (current gain of BJT)   * So, in active region we can say that doesn’t affect that much and for the fix value of behaves like a const current source – thus BJT in this common base config with it working in active region acts as   an amplifier   * output impedance will be very high as over is almost 0 – making very high   **saturation region**     * Here when we forward bias the Vcb junction : the collector current start decreasing   **Cutoff region**     * Here when we remove Vbe , the current 0 which also makes 0 (the only collector current exist is due to minority charge carriers (reverse saturation current) (     Common base config application : voltage Amplification  Note : for simplification DC biasing voltages are not shown     * The input impedance in the common base config is very low(in ohms) * Here we have assumed   + - = 5mV     - 10 ohms (input impedance)     - = = 0.5mA     - 100 k ohms (output impedance)     - 1 k ohms * Now consider that * So, using formula 🡪 it is said that will be equal to * This means output current will be same as * For common base config output impedance is very high (in Kilo ohms) * = = 0.5 mA \* 1000 ohms = 0.5v * The input voltage was 5mV which has been amplified to 0.5V = 500mV (100x amplification) * However, the current gain here = < 1   Note : Voltage gain in this type of common base volt amplifier is around 50x to 300x | | **Common Emitter config**    To use BJT as amplifier Base-emitter junction is forward bias and collector-base terminal is reverse biased    Also, can be represented like this along with the direction of current      **Input characteristics**  defines the behaviour of and considering constant       * Here as increases - decreases : this is because = + (and is const) – meaning to increase in means increase In (as the reverse bias increases – depletion region becomes wider (the base region becomes thin) and thus current decreases) * Input impedance ( **delta IB is large** for small change in VBE → **input impedance is low** (it's a forward-biased junction, like a diode!))   **output characteristics**  defines the behaviour of and considering constant    This can be divided in 3 regions   1. Active region 2. Cutoff region 3. Saturation region   **Active region**     * Here when increases : also increases and similarly when increases also increases * The reason is = + (and is const) – meaning to increase in means increase In (as the reverse bias increases – depletion region becomes wider (the base region becomes thin) and thus more current can flow from through Base region increasing * Input impedance = * Current gain = (where ) * Voltage gain Av = [-ve shows 180֯ phase shift] [if u use bypass cap across Re (which lets AC signal shunt to gnd -- is considered 0) * Here = internal emitter resistance = [*thermal voltage ≈* ***25 mV*** *at room temperature (fixed) ]* * Benefits of common Emitter mode     **saturation region**     * Here both base – emitter and collector – base junction is forward bias   **cutoff region**     * Here both collector base and base – emitter are reverse biased (and = 0)      * When is 0 : |  |  | | --- | | **Common collector config**    **🔹 What is Common Collector (CC) Configuration?**  In the **CC configuration**, the **collector terminal is common** to both input and output.   * **Input is applied** between **Base and Collector** * **Output is taken** between **Emitter and Collector** * Often used as a **buffer** due to **high input and low output impedance**   **Input characteristics**  Between and      Here , Vce = Vcb + Vbe (for the fix value of Vbe = 0.7)  As the Vcb increases , Vce also increases (making depletion region wider and base area small) and Ib decreases    Here for the fix value of Vcb – when Vce increases (base current also increases)  Current gain () = = (1 + ) = ( )  Also  **Output characteristics**  Between and    Here , = (but 1) thus    Due to high input impedance and low op impedance, it can be used in impedance matching  Current gain () = = (1 + )  Voltage gain 1 | |  |       **Working of BJT in active region (explained using NPN transistor)**     * Here keep in mind (emitter is heavily doped, base is lightly doped and collector is moderately doped) * Now when is applied to base-emitter junction and is a forward bias (i.e. )      * Emitter has lot of free electrons – which moves towards base (which is lightly doped-hence low holes) – so few of the electrons recombine with them and flow in Emitter -> Base -> Rb -> Vbb path * Additionally , due to thin base region and being in reverse bias – the pull of is higher for collector electrons and emitter electrons – so a good amount of electron will cross base and will flow through this path : Emitter -> base -> collector -> -> Rc -> Vcc path * So, the direction of the flow of electron   + - Small amount of electron flow (Emitter to Vbb)     - Large amount of electron flow (Emitter to Vcc) * However, the conventional current will have this path     Applying KCL 🡪  Therefore 🡪 (here = multiplier value)  After lot of calculation    Here = gain of BJT  **This means if we can control input current we can control output current (that is why BJTs are called as current controlled device)**  **Note : if you connect a resistor across C and E and take Vout from there – and apply AC signal between B and E – you can get amplified signal at the output (this shows in active region – BJT can work as amplifier)** |
| Q point (Quiescent Point) and DC – AC analysis | * **DC analysis** → it's done to **find the Q-point**, the sweet spot in the **active region** * Q-point = where transistor **amplifies cleanly**, without cutting (cutoff) or crushing (saturation) the signal * **Q-point calculation** includes finding **IC,IE,IB,VCB**etc. * **AC analysis** → It checks the **small-signal gain** (and other dynamic behaviours)   **🔧 Minor additions to strengthen your base:**   * **DC analysis is purely for setting up the "no signal" condition** → biasing the transistor when input AC = 0 * Q-point is often represented as a pair:      * **AC analysis** also gives you:   + **Input resistance Rin**   + **Output resistance Rout​**   + **Voltage gain Av**   + **Current gain Ai** (These help in amplifier design and cascading)   **🔍 What is the Q-Point?**  **Q-point = Quiescent Point** It’s the **DC operating point** of a transistor — where it “sits” when **no AC signal is applied**.  **🧭 Think of it as:**  “The stable **starting point** of a transistor — set by biasing — from where it can respond cleanly to AC signals.”  **📐 What does it define?**  The Q-point gives the **DC values** of:   * ​ → Collector current * ​ or → Voltage across collector and emitter/base * ​ , → Base and emitter currents (if needed)   **📈 Where is the Q-point *placed*?**  The Q-point is a **single point on the transistor’s output characteristic curves**, usually chosen to:   * Keep the transistor in the **Active region** (for amplification) * Avoid distortion due to **saturation or cutoff** * Allow maximum possible **signal swing**   **🎯 Why is Q-point important?**   | **Without Signal** | **With Signal** | | --- | --- | | Transistor rests at Q-point | Signal causes it to vary around Q | | Q-point too low → signal clips at **cutoff** |  | | Q-point too high → signal clips at **saturation** |  | | Good Q-point → **smooth amplification** |  |   **🧠 Visual Analogy:**  Imagine a swing set:   * The **Q-point is like the person’s rest position** * An AC signal is like giving the swing a push * If they start from a good middle spot (Q-point), the swing goes both sides smoothly * If they start too far forward/back, they’ll hit a wall (distortion = cutoff/saturation)   **💡 Summary**   | **Term** | **Meaning** | | --- | --- | | Q-point | DC bias point (without input signal) | | Region | Usually in **Active region** | | Purpose | To allow clean amplification | | Set By | Biasing resistors & power supplies |   **DC Analysis (CB Configuration)**  **🔌 Given:**   * NPN transistor (Silicon → VBE = 0.7V) * VEE=2V * RE=1kΩ * RC=2kΩ * VCC=10V * β=100   **🎯 Objective:**  Find the **Q-point**:   * ​ (Emitter current) * ​ (Collector current) * VCB ​ (Collector–Base voltage)         **✅ Final Q-point:**   | **Parameter** | **Value** | | --- | --- | | IE | 1.3 mA | | IC | ~1.287 mA | | VCB ​ | 7.426 V |   This Q-point lies in the **active region** since:   * VCB>0 → **Collector is more positive than base** * VBE=0.7V→ **Emitter forward biased**   **AC Analysis (CB Configuration)**  Recap from Previous Q-Point:  From our DC analysis:   * IC=1.287 mA * RC=2kΩ * VT=25 mV |
| AC and DC analysis of transistor | **why learning DC and AC analysis of transistors (like CB, CE, CC)** is *essential* for VLSI and electronics.  **🔌 Why DC Analysis Matters**  **🎯 Purpose: Set the transistor's Q-point**  That means:   * Ensuring the transistor is **in the correct region** (Active, Cutoff, or Saturation) * Setting up **biasing circuits** to keep behavior stable despite temperature changes or signal fluctuations   **💡 Why it’s important:**   | **Without DC Analysis** | **You Risk** | | --- | --- | | Transistor may sit in **cutoff/saturation** | No amplification, signal clipping | | Bad biasing → **wrong Q-point** | Distorted output or complete failure | | VLSI chips with 1000s of transistors | Need stable biasing to function reliably |   **🌊 Why AC Analysis Matters**  **🎯 Purpose: Understand how the transistor responds to small signals**  **📈 You Learn:**   * How much the transistor **amplifies** the signal (gain) * What’s the **input/output resistance** * Whether the **signal gets inverted** or not * How to **design amplifiers** with desired performance   **💡 Why it’s important:**   | **Without AC Analysis** | **You Risk** | | --- | --- | | No control over **gain** | Your amplifier may be too weak or distorted | | Wrong impedance match | Poor signal transfer between stages | | No understanding of bandwidth | Circuit fails at high frequencies (important in VLSI) |   **🧠 Real-World Relevance**   | **In Domain** | **Why It Matters** | | --- | --- | | 💻 VLSI Design | All digital logic is built using transistor-level models. You *must know how they behave*. | | 📱 Analog/RF | Amplifiers, filters, sensors – rely on solid DC/AC analysis. | | 🛠️ Debugging | If a transistor isn’t working in a circuit, DC/AC analysis helps **pinpoint the issue** | |
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| **Q-Point (DC) + AC Analysis for CE Configuration** |  |
| Transistor basics (RECAP) (IMP stuff) |  |
| **BJT in saturation region** | When we use BJT as switch operating point changes from cutoff to saturation and vice versa  To identify operation of BJT in cutoff is easy     * When base volt is Vbb= 0 (or u can say Vbb < VBE (0.7v for semiconductor BJT) ), then Ib = 0 * 🡪 0 ( neglecting the reverse saturation current ) * And as = 0 , no volt drop occurs at Rc –hence Vcc appears at collector terminal * But when Vbb is non zero we cannot clearly determine that whether it is active or saturation region * So, the Q point would be lying something around here (in the cutoff region basically)     Thus, we can say that when Ib = 0 , Ic is also 0 + Vce = Vcc (meaning BJT is operating in the cutoff region)  To identify operation of BJT in Saturation region     * Assuming , Voltage Vce in saturation is almost 0 ( (but in actual it is between 0.2 to 0.3v – due to junction barrier) * As the , collector current is maximum ( ) * If it is said that BJT is in the saturation region   Steps to identify BJT is in saturation or not   * Consider * The find the value of * Find the value of * now consider transistor operating in active region so = ( u get the value of ) * if > (it confirms that BJT is in saturation region)     Example    Here,  = 50   * here considering * = = 0.002 Amp = 2mA * = = 0.000093 Amp = 93uA * = = 50 \* 93uA = 4.65mA * Here , > (this ckt is currently in saturation region)   Note : in saturation region lets calculate current gain = 21.5  Which shows that in saturation region changes ( < )  Hard Saturation   * For the known values of and , the value of should be selected in such a way that the transistor current gain is very low in the saturation (this is called hard saturation) [this ensures that even if the external parameter changes BJT remains in the saturation mode * <     Let’s calculate value such that this BJT sits in the hard saturation   * from the above example 2mA * = 10 (we want to achieve this) * = = 200uA * 200uA base current will ensure the transistor is in the saturation region * = = 46.5 k |

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| **BJT as a switch** | Operating BJT in cutoff and saturation region we can use it as switch    **Operation of BJT when pulse signal 0 to 10v is applied**   1. When 0v signal is present at base      * Here = 0 , thus = 0 and 0 * So, at the collector terminal Vcc appears (as no drop happens across Rc due to Ic being 0) * The resistance between C and E is * Here as 0 , R becomes * Making transistor act as an open ckt between C to E terminal (note : in actual there flows some reverse saturation current but in that case as well , the Resistor R becomes very high)      1. When 10v signal is present at base      * Let’s just check whether this is in saturation or not   = = 2mA  = = = 186 uA  = = 50 \* 186uA = 9.3mA     * Here (confirming that the BJT is in saturation region) * In saturation region of operation, we assume that 0 * Resistance between C and E terminal R = = 0 * Making it act like a short ckt * In reality – in saturation region the is around 0.2 to 0.3v (making R very low)        * Here u can see – * When **base = 0V** → transistor is **OFF (in cutoff)**, V(collector) = Vcc (load gets no current) * When **base = 10V** → transistor is **ON (in saturation)**, V(collector) ≈ 0.2V → current flows through load |
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|  | \      BJT requires current at the base (BJT is current controlled device)  MOSFET requires voltage at the Gate terminal (MOSFET is voltage-controlled device)  MOSFET can handle much more current compared to BJT  **Experiment**     * Do this setup * Now connect the purple wire to red cable points (or to +ve supply of battery)      * Bulb turns on * If we now immediately open purple wire * The bulb will still be open as mosfet stores charge (acts as a capacitor) unless we provide it a path to use/dissipate this stored charge (we can connect the pin to gnd to dissipate the stored charge) (the MOSFET will be deactivated)     **Inrush current** :  MOSFET does not have any current flowing in Gate terminal when ON or OFF (but it does draw some current when turned ON from OFF) which is called inrush current  \    Example :      Two main types of MOSFET   1. Enhancement type 2. Depletion type |
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|  | 1. Enhancement MOSFET (Normally OFF)  |  |  | | --- | --- | | **N- channel Enhancement** | **P- channel Enhancement** | |  |  |  1. Depletion MOSFET (Normally ON)  |  |  | | --- | --- | | **N- channel Depletion** | **P- channel Depletion** | |  |  | |
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