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Analytical and Simulated Study of a Bipolar Transistor's Input Characteristics Using NI Multisim 14.2 Program

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ABSTRACT

Objective: *This research presents a comprehensive study of the input characteristics of an NPN transistor in a common-emitter configuration using NI Multisim 14.2 at a constant output voltage across the transistor ($V_{CE} = 2\,V$).* ***Method:*** *The research methodology focuses on the increase in base current (I_B) as a result of the voltage increase (V_{BE}). The switching voltage, i.e., the critical operating point, is determined using the dynamic resistance equation.* ***Results:*** *The results obtained from NI Multisim 14.2 and the mathematical equations for a silicon diode that accepts or consumes a lower voltage (approximately 0.8 V) are crucial.* ***Novelty:*** *The most important conclusion of this research is that these calculations, relating to base current, emitter-base voltage, and a low dynamic resistance (7.58 Ω), form the basis for designing electronic circuits and the switching and amplification processes they undergo.*

INTRODUCTION

The bipolar junction transistor (BJT) is one of the most important electronic components that has kept pace with technological advancements and revolutionized the world of electronic circuits. This component facilitated the transition from large, inefficient vacuum tubes to small, highly efficient electronic components and devices [1], [2]. The BJT relies on a mechanism to control the output current, which is controlled by the input current. Therefore, it is clear that the transistor is current-dependent [3], [4]. The electrical characteristics of the BJT, in terms of study and analysis, are divided into two main categories: input characteristics, which study the dynamic relationship between the base current and the base-emitter voltage when the collector-emitter voltage is constant; and output characteristics, which focus on tracking the relationship between the collector current and the collector-emitter voltage when the base current is constant [5]. These characteristics and the importance of the transistor make it suitable for use as an electronic switch and for amplifying weak signals in audio processing and communications. To understand its bias in a common-emitter configuration, it is necessary to understand the operation of the forward bias region of the base-emitter junction, which has the same practical behavior as a conventional diode [6]. However, the difference here lies in the clear and direct influence of controlling the output voltage and its stability. The importance of the input characteristics is related to determining the input impedance [7]. In addition, the characteristics of the transistor are greatly affected by the movement of the minority and majority charge carriers, as well as by even slight thermal changes. Therefore, engineers and manufacturers are forced to design electronic circuits that allow the transistor to operate without being exposed to thermal changes [8]. With the advancement of modern computer simulation programs, most notably NI Multisim 14.2, researchers and engineers can now virtually build and design circuits, extract results with high accuracy and without losses, and plot curves before conducting practical laboratory applications. This increases the likelihood of accurate results, reduces the error rate, and protects electronic components and circuits from damage caused by high voltages and currents [9]. This research aims to provide an integrated analytical study and computer simulation of the input characteristics of an NPN transistor in a common-emitter configuration, which is the most common and widely used configuration in practical circuits due to the high and significant gain it provides in both voltage and current, with a focus on monitoring the current behavior at the operating point and calculating the governing dynamic resistance of the input.

Theoretical aspect

In a common-emitter connection, the base-emitter junction becomes a forward-biased diode. Therefore, the input characteristics are expected to behave exactly like a diode's characteristic curve, and the base current I_B is related to the base-emitter voltage V_{BE} according to the modified Shockley Diode Equation [10], [11]:

$$I_B = I_{B\circ}\, exp\left(\frac{q\, V_{BE}}{\eta\, k\, T} - 1\right) \qquad (1)$$

Whereas: $I_{B\circ}$: Reverse saturation current of the base, q: Electron charge 1.6×10^{-19} C, k: Boltzmann constants 1.38×10^{-23} J/K, T: Absolute temperature in Kelvin and η: Ideality factor.

When the applied input voltage V_1 is less than the silicon barrier potential, the current I_B is very small (in picoamperes or nanoamps). Once this voltage is exceeded, the current increases exponentially [12], [13].

The dynamic input resistance is defined as the ratio of the change in base-emitter voltage to the change in base current at a specific operating point (Q-point) [14].

$$R_{in} = \left.\frac{\Delta V_{BE}}{\Delta I_B}\right|_{V_{CE}=constant} \qquad (2)$$

Whereas: ΔV_{BE} : the difference between the emitter-base voltage and ΔI_B : the difference between the base current.

RESEARCH METHOD

The electronic circuit shown in Figure (1) was constructed using the NI Multisim 14.2 engineering simulation program, with the following components:

A. Input Voltage Source (V_1): A variable DC voltage source, representing the applied voltage, which is gradually increased from 0 V to 5 V.

B. Base Protection Resistor ($R_1 = 39\Omega$): Used to limit and regulate the base current and prevent transistor damage at high voltage intervals.
C. Collector protection resistor ($R_2 = 1\text{k}\Omega$): Used to limit the collector current and prevent transistor damage at high voltages.
D. A hypothetical NPN bipolar transistor.
E. Voltage source (V_2): A constant voltage source to maintain the collector-emitter junction bias at approximately a constant value at $V_{CE} = 2$ V. This voltage is maintained by controlling the voltage source V_2.
F. Measuring Instruments: A digital ammeter connected in series to measure the base current I_B. A digital voltmeter connected in parallel between the base and emitter to measure V_{BE} Also, a digital voltmeter connected to the two ends of the transistor to measure the voltage V_{CE}.

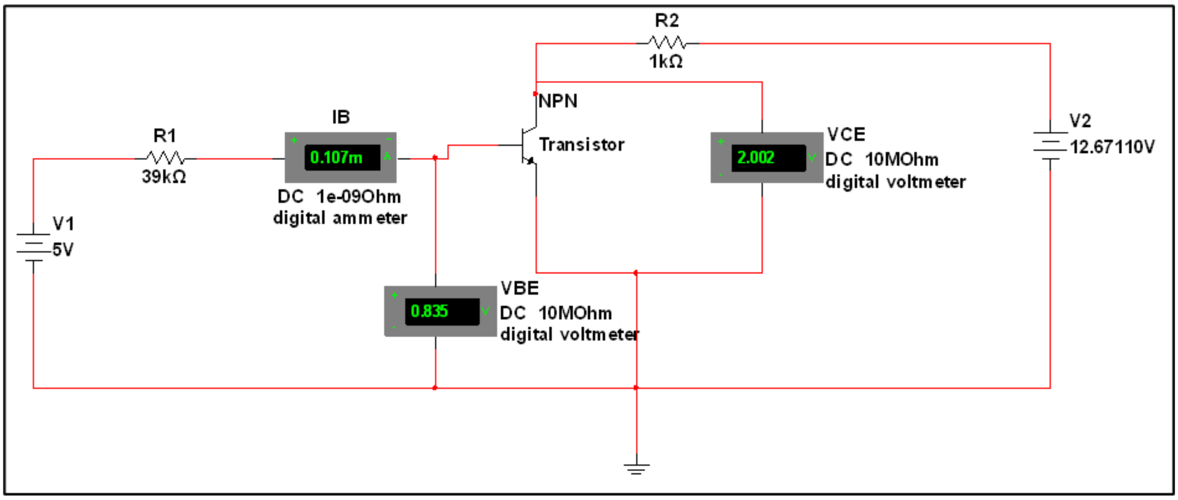

Figure 1. Shows the electronic circuit designed using NI Multisim 14.2 program at an applied voltage of $5V$.

RESULTS AND DISCUSSION

The practical readings resulting from the simulation were recorded in Table (1) at a constant value for the output voltage $V_{CE} = 2$ V.

Table 1. Results obtained from the NI Multisim 14.2 program for base current I_B and junction voltage V_{BE} at a constant output voltage $V_{CE} = 2$ V.

Applied Voltage V_1(V)	Base-Emitter Voltage V_{BE}(V)	Base Current I_B(mA)	State & Physical Analysis [15], [16]
0	0	0	The transistor is in total Cut-off state.
0.2	0.199	0.000028	Very weak forward bias, below the threshold voltage.
0.4	0.298	0.000056	Current is still negligible (Idle/Dead zone).
0.8	0.729	0.00188	Threshold voltage exceeded; actual onset of current conduction.

1	0.761	0.006106	Clear exponential growth in current with relative stability in V_{BE}
2	0.78	0.031	Transistor is in the Active Region.
3	0.79	0.56	Input current increases proportionally with the applied voltage.
4	0.80	0.08	Junction voltage V_{BE}stabilizes around $0.8V$
5	0.835	0.107	High current, and the junction is operating at full efficiency.

Mathematical and Physical Analysis of the Results

From Figure (2), we observe that increasing the V_{BE} results in an increase in current with an approximate constant collector - emitter voltage. The process of voltage and current increase can be divided as follows.

A. Low Potential Region $V_1 \leq 0.4$ V: We observe that the V_{BE} voltage rises almost following the V_1 because the internal resistance of the base-emitter junction is very high (open circuit), and therefore the I_B current is almost zero.

B. Knee or Threshold Region $0.4 < V_1 \leq 1$: At the point $V_1 = 0.8$ V, we observe that the V_{BE} voltage stabilizes at $0.729V$, which is the voltage to overcome the silicon depletion region. Here, the I_B current begins to jump significantly from $0.000056\ mA$ to 0.00188 mA.

C. Linear/Exponential Conductivity Region $V_1 > 1$: The table shows a very important physical phenomenon in BJTs; While the applied voltage V_1 increases from 1V to 5V, the base-emitter voltage V_{BE} rises very gently and slowly from (0.761V to 0.83 V), while the base current I_B jumps dramatically from (0.006106mA to 0.107 mA). This demonstrates the exponential behavior of the input junction.

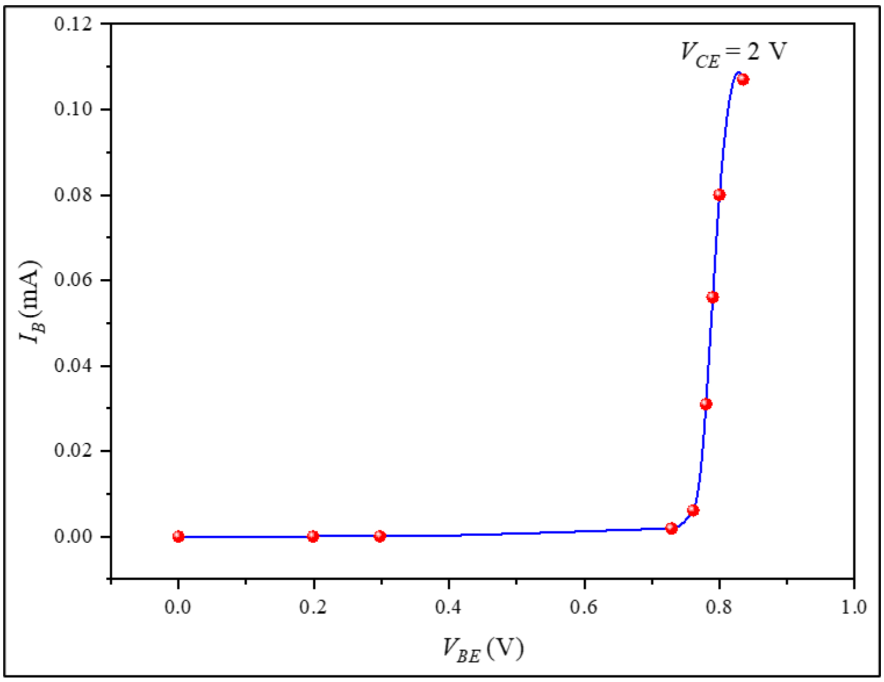

Figure 2. Shows the input characteristics of the transistor between V_{BE} various I_B.

And to Calculating the Dynamic Input Resistance R_{in}, then we will take the difference between the emitter-base voltage equals: $\Delta V_{BE} = V_{BE2} - V_{BE1} = 0.761 - 0.729 = 0.023$ V, and the difference between the base current equals: $\Delta I_B = I_{B2} - I_{B1} = 0.006106$ mA $-$ 0.00188 mA $=$ 4.226×10^{-3} A, and by substituting in equation (2), we obtain: $R_{in} = \left.\frac{0.023V}{4.226 \times 10^{-3}\,A}\right|_{V_{CE}=2} = 7.58\Omega$

From this result it is evident that the dynamic input resistance is very small when the transistor is in the active forward conduction state, which is a key feature of the common-emitter configuration.

CONCLUSION

Fundamental Finding : Through the analytical study of the input characteristics of the bipolar junction transistor in a common-emitter configuration, we conclude that the base-emitter junction behaves in a forward-biased configuration, where the base current I_B remains zero in the cutoff region until it exceeds the threshold voltage of 0.729 V. We also conclude that the relationship between I_B and the voltage V_{BE} is exponential, governed by the Shockley equation. This explains the enormous jump in the base current from 0.00188 mA to 0.006106 mA when the voltage changes by a very small amount, not exceeding 0.032 V. Mathematical calculations show that the input dynamic resistance drops sharply to a very small value of 7.58 Ω in the active region, giving the circuit exceptional sensitivity to small-scale signals. Furthermore, the dynamically stable V_{BE} junction voltage is observed at around $0.8V$ as the source voltage V_1 gradually increases from (2 V to 5 V), where the protection resistor absorbs the over voltage. Finally, the simulation via the NI Multisim 14.2 program proved to be in complete agreement with the mathematical physical model, allowing for the extraction of transistor parameters with extreme accuracy and without the risk of damaging the electronic junction. **Implication :** These calculations imply that establishing highly precise threshold parameters enables engineers to optimize power efficiency and prevent thermal runaway in dense semiconductor layouts. Consequently, circuit designers can reliably predict switching latencies and signal amplification thresholds before manufacturing physical prototypes. **Limitation :** A key limitation is that this study relies entirely on an idealized NI Multisim environment running a standard Shockley model equation under perfectly constant ambient temperatures. It does not account for real-world hardware non-idealities, such as parasitic capacitance, manufacturing tolerance variations, or high-frequency signal degradation. **Future Research :** Future research should evaluate these transistor input characteristics under extreme temperature fluctuations and high-frequency operating conditions using real laboratory hardware. Additionally, subsequent studies could expand the simulation to analyze alternative configurations, such as common-base and common-collector layouts, across varying load resistances.

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